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of Malé Karpaty focal zone
using seismic noise spectral H/V ratio“

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Declaration

I hereby declare that this Master`s thesis is my own work, under the supervision of my thesis supervisor. And that I have not used any sources other than those stated in the thesis.

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Introduction

Submitted work focuses on analysis of seismic noise recorded by permanent seismic stations of local seismic network Malé Karpaty by H/V spectral ratio method. Obtained results will be compared with theoretical SH transfer functions and ellipticity curves computed for existing seismic model of Malé Karpaty and differences will be analyzed.

The area Malé Karpaty is one from the most important epicentral sites at Slovakia. On the one hand it is the most active site at Slovakia and on the other hand it is in close proximity to nuclear power plant Jaslovské Bohunice. Thoroughly evaluation of seismic hazard of this site is essential. For correct evaluation of seismic hazard good knowledge about model of local geological structure is needed. Geological structure of the Male Karpaty source zone is very complicated and the current seismic model is not sufficiently accurate.

The spectral ratio H/V of seismic noise should make possible to find out the spatial variability of local geological structure and to help to identify the parts of the current model, where it differs from reality. In this purpose we will compare H/V curves from permanent seismic stations of Malé Karpaty source zone with theoretical SH transfer functions and ellipticity curves computed for current seismic model of this source zone.

Since for correct interpretation of results obtained by analysis of seismic noise is essential and very important a good understanding of a nature and a composition of the seismic noise wavefield and also his variability for various localities and under various conditions, the part 1 of this work is focused on this problematic. In the Section 2 are formulated aims of out diploma`s thesis and the following section 3 is focused on more detailed description of the H/V spectral ratio method, its computational principle, theoretical explanation, importance of various parameters and the factors which are important for correct interpretation of results. Section 4 contains results of our master`s thesis, which are divided into several subsections. In the last section are summarized the conclusions of our work.

1 State of the art

1.1 Seismic noise

In this section we introduce the term seismic noise and discuss the origin, nature and the composition of the seismic noise wavefield.

The seismic noise denotes relatively persistent weak vibrations of the ground caused by many sources of different types, for example: tides, waves striking the coast, traffic, industry, human activity, meteorological conditions and so on.

During the last few decades a role of the seismic noise changed from the useless and even undesirable part of the seismic signal to the useful source of information. It is a consequence of development of the new methods which allow obtaining information about local geological structure from the records of seismic noise. Seismic noise recordings represent a very useful and extensive data set, especially for countries with relatively low level of seismic activity and absence of sufficient number of earthquakes. Such a country is also Slovakia. Since the seventies up to present, the number of seismic noise studies increased dramatically. The majority of studies just applied different analysis methods to noise recordings in order to retrieve information about local geological structure and site effects. Fewer papers studied also applicability of the methods under different conditions and/or carefully analysed and interpreted results with regard to noise wavefield composition.

1.1.1 Origin of seismic noise

Permanently present ambient vibrations on seismic recordings are composed of composed of man-made ground motions superimposed with natural ground motions. Due to different source types these two basic parts of noise ground motion differ in the frequency content. This difference led to distinguishing basically between microseisms and microtremors. Some authors introduce as well the transitional range (*J. C. Groos and J. R. Ritter, 2009*).

1.1.1.1 Microtremors

Higher frequency part of seismic noise wavefield with frequencies above 1 Hz is usually denoted as microtremors. Seismic noise at these frequencies clearly depends on human activities (e.g. *Kanai and Tanaka, 1961; Okada, 2003; Bonnefoy-Claudet, 2004*), thus on people walking, factories, traffic, machinery and so on. Daily and weekly variations connected with human activities can be observed in their spectral amplitudes (*J. C. Groos and J. R. R. Ritter, 2008; Guillier et al., 2007*). Cultural noise propagates mainly as high-frequency surface waves and is attenuated within several kilometres in depth and distance (*McMamara and Buland, 2004; Bonnefoy-Claudet et al., 2006*).

Presence of transient events and monochromatic waves in microtremors, produced by close proximity anthropogenic sources, often causes complications in the seismic noise analysis.

1.1.1.2 Microseisms

Some authors qualify frequency band 0.6 – 1 Hz as a *transitional range*. In this frequency band, both types of anthropogenic and natural sources are involved. Local wind conditions and wind-induced oscillations of structures and buildings are the most important sources of noise in the transitional range (*J. C. Groos and J. R. R. Ritter, 2009*).

Lower frequency part of seismic noise wavefield under 1 Hz, generally produced by natural sources, is usually denoted microseisms. Because of their natural origin, microseisms are not affected by daily variations due to human activities. Seismic noise at frequencies around 1 Hz is related to wind effects and local meteorological conditions and noise below 0,5 Hz is generated by oceanic and large scale meteorological conditions. Amplitude variations at these frequencies are mainly linked with variations of natural phenomena, most often oceanic activity for long period noise (*S. Bonnefoy-Claudet et al., 2006*). When oceanic waves impact the coastline, part of their energy is transferred into seismic waves known as microseisms. The energy transfer can occur via three different ocean wave mechanisms in different frequency bands (*James Traer et al., 2011*).

Double frequency (DF) microseisms have double frequency of ocean waves (0.15 – 0.5 Hz). The generation of DF microseisms requires significant reflection of wave energy from the

coasts. Part of the energy which impacts coastline is reflected back to the ocean where it can interact with incident waves travelling in the opposite direction. Standing wave, with double frequency of the propagating ocean surface waves, is raised. The amplitude of standing wave stays nearly constant with depth and at the seafloor is transformed into seismic waves, further propagating in the oceanic crust.

Primary microseisms (PM) occur at the same frequency as the ocean waves that generated them, i.e. 0.02 – 0.17 Hz. PM are generated when oceanic waves impact the coast, part of their energy is transferred into the crust.

Hum is a low amplitude signal at the frequencies lower than others types of microseisms (0.002 – 0.02 Hz). It is generated by long periodic infragravity (IG) waves with periods 50 – 450 s and wavelengths of the order of kilometers. IG waves are generated by nonlinear transformation of the part of the incident energy of long period oceanic waves. Interactions of IG waves produce hum signals by the same mechanism as DF microseisms (*James Traer et al., 2011*).

1.1.2 Wave composition of the seismic noise

Thorough understanding of seismic noise wavefield composition from the physical point of view is essential for correct application of methods of seismic noise analysis and for a reliable interpretation of the obtained results. In the following subsections we discuss the two possible, but different ways how to consider the composition of noise wavefield: in terms of relative contributions of individual wave types (subsection 1.1.2.1) or, noise wavefield considered as a diffuse field (subsection 1.1.2.2).

1.1.2.1 Noise as a wavefield with relative proportion of different types of seismic waves

In this part we discuss seismic noise wavefield composition in terms of the relative proportion of surface waves and body waves, relative proportion of Rayleigh waves and Love waves and the relative proportion of fundamental and higher modes of Rayleigh waves.

The relative proportion of surface and body waves

Contribution of various wave types in seismic noise was investigated firstly in sixties by *Toksöz and Lacoss (1968)* and *Douze (1964, 1967)*. These studies investigated the noise wavefield in a relationship with crustal waves for rocky sites.

In eighties, *Li et al. (1984)* and *Horike (1985)* studied wave composition of seismic noise at sedimentary sites. *Li et al. (1984)* state that that the noise wavefield in the frequency range 1 - 20 Hz is composed of P-waves and of higher modes of Rayleigh waves. According to *Horike (1985)*, noise in the frequency range 0.5 – 0.9 Hz consists of fundamental Rayleigh waves, while at higher frequencies between 0.9 – 3 Hz also higher modes of Rayleigh waves can occur.

Comparison between observed H/V curve from measurements and theoretical ellipticity curves of the fundamental mode of Rayleigh waves for sedimentary sites was discussed by *Yamanaka et al. (1994)*. Results showed that microseisms in frequency range 0.1 – 1 Hz have been composed of fundamental mode of Rayleigh waves mainly.

Also *Bonnefoy-Claudet (2004)* compared H/V curves with ellipticity curves of the fundamental mode of Rayleigh waves but for synthetic seismic noise computed for various horizontally layered media. Her conclusion is that surface waves are dominated in noise wavefield only in the case of large impedance contrast. The wavefield contains also body waves in the case of smaller velocity contrast.

Sensitivity of the noise wavefield composition on the sources properties is shown in later works of *Bonnefoy-Claudet et al. (2006, 2008)*. *Bonnefoy-Claudet et al. (2006)* applied H/V and array analyses to vertical components of synthetic seismic noise in the case of high impedance contrast media, one soft layer over a half-space. According to this study the relative proportion of Rayleigh waves to body waves is related to the spatial distribution of noise sources: (1) If the sources are close (4 – 50 times the layer thickness) and surficial, noise wavefield consists mainly of fundamental mode of Rayleigh waves. (2) When sources distance is more than 50 times the layer thickness and sources are within the sedimentary layer, noise wavefield is composed of fundamental Rayleigh waves and head S waves. (3) In the case of sources located inside the bedrock, mainly non-dispersive body waves are present in the noise. *Bonnefoy-Claudet et al. (2008)* extended previous analysis for various horizontally layered media with different impedance contrasts and not just for the vertical

component but as well as for the horizontal components of seismic noise. They show that relative contribution of various wave types depends significantly on the impedance contrast. (1) For high-impedance contrast the noise contains fundamental modes of Rayleigh and Love waves. (2) For moderate-impedance contrast fundamental mode of Love waves is dominant and the fundamental mode of Rayleigh wave also occurs. (3) In media with low-impedance contrast is wavefield formed mainly by fundamental mode of Love waves and by body S waves.

Koper et al. (2010) performed a global survey of Earth's seismic noise wavefield using f - k method on vertical component data from 18 seismic arrays, focused on short-period frequency band with periods 0.25 - 2.5 s (0.4 – 4 Hz). They found out that noise wavefield comprised three predominant wave types: 50% L_g , about 28% of P-waves and approximately 23% consists of fundamental mode of Rayleigh waves (R_g).

The relative contribution Rayleigh and Loves waves in seismic noise wavefield

Ohmachi and Umezono (1998) used numerical approach, they simulated propagation of the noise in 1D models. They used coherence value between radial and vertical synthetic noise components as a good estimation of the Rayleigh to Love waves proportion. The results of their coherence analysis shows that proportion of Rayleigh and Loves waves in synthetic data is strongly dependent on the type of excitation, on the impedance soil contrast and on the observation direction. According to this paper ratio of Rayleigh to Love waves varies from 10% to 90%, with average roughly 30%. Since the results from their numerical approach were strongly affected by orientation of the random sources, they do not provide quantitative estimate of the relative proportion of Rayleigh to Love waves in real seismic noise wavefield.

Another approach for estimation of the Rayleigh to Love waves ratio in the seismic noise is based on array measurements. *Chouet et al. (1998)* studied the properties of volcano tremor by spatial auto-correlation array method SPAC (developed by *Aki, 1957*). Rayleigh and Love wave phase velocities were obtained by inverting the spatial auto-correlation curves. This approach is more interesting from the methodological point of view than because of the results themselves, since the volcanic tremors and the seismic noise have

wavefields with different properties. Results showed that 77% of total energy of the volcanic tremor came from Love waves, and 23% from Rayleigh waves.

Later, other authors also used SPAC method to derive relative contribution of different surface wave types in the seismic noise. *Yamamoto (2000)* concludes that more than 50% of seismic noise energy is carried by Love waves for urban sites and frequency range of 3-8 Hz. *Okada (2003)* shows that proportion Rayleigh to Love waves varies from 50% to 90% for long period waves with periods from 1s to 3s. *Köhler et al. (2007)* estimates the proportion of Love waves values 65-90% in the case of intermediate frequencies from 0.05-1.3 Hz. *Arai and Tokimatsu (1998, 2000)* also used f - k analysis besides the SPAC method. From both methods they obtained similar results. In the frequency band from 1 Hz to 12 Hz, average value of the ratio of Rayleigh to Love wave energy was 0.7. It means that cultural noise at investigated sites in Japan consists of approximately 40% of Rayleigh waves and 60% of Love waves.

Cornou (2002) and *Cornou et al. (2003a, b)* investigate deep basin in Grenoble with the MUSIC high resolution array analysis (*Schmidt, 1981*). By the ratio of the energy of the radial and transverse components they estimated the proportion of energy carried by Rayleigh waves. In the frequency band from 0.2 Hz to 1 Hz, the proportion of Rayleigh waves was around 50% (*Cornou, 2002*).

As can be seen from the overview above, there is no clear conclusion about proportion of different types of surface waves in the seismic noise wavefield in general. Various studies were done for different sites with different sediment thickness and different noise sources and the results are very site-dependent. According to *Bonnefoy-Claudet (2006)* the site geometry (sediment thickness, geometry of interface, slope) together with geology, and with the source properties (*see also Ohmachi and Umezono, 1998*) can influence presence and the proportion of different types of surface waves in the seismic noise wavefield. According to *Bonnefoy-Claudet (2006)*, the best way to determine the relative proportion of Rayleigh and Love waves seems to be 3-component array analysis, especially SPAC method (*e.g. Okada, 2003*). Overview of the methods suitable for seismic noise analysis is provided in more detail in the section 1.2.2.

Relative contribution of the fundamental mode of Rayleigh waves

Content of fundamental and higher modes in seismic noise wavefield and/or their relative proportions are less often investigated in literature.

E.g., *Tokimatsu (1997)* suggests that higher modes of Rayleigh waves exist in seismic noise, but he does not provide quantitative information about their proportion in the noise and he consider soil stratification to be the important factor in higher mode excitation.

Some indirect information about contribution of the fundamental mode of Rayleigh waves was retrieved from H/V curves analysis (*Stephenson, 2003; Konno and Ohmachi, 1998*). Authors show, that if seismic noise contains only fundamental mode of Rayleigh waves then H/V curves have peak or trough structure.

Bonnefoy-Claudet (2004), contrariwise, in numeric simulations have never noticed such a peak or trough structure of H/V curves. Analysis performed on synthetic seismic noise points out that both fundamental and higher modes of Rayleigh waves are present in the most types of media simultaneously. In the most of cases a peak/ trough structure is not observed in H/V curves because of existence of higher modes at the frequency corresponding to the vertical polarization of the fundamental mode of Rayleigh waves (the “trough frequency”) (*Bonnefoy-Claudet, 2004*).

Several studies deal with the origin of the second, or third peak on H/V curves (*Bodin et al., 2001; Asten and Dhu, 2002; Asten, 2004; Bonnefoy-Claudet, 2004*), but in this topic is no common conclusion. *Bodin et al. (2001)* interpret second peak of H/V from Memphis basin as caused by first higher mode of Rayleigh waves. According to the papers of *Asten and Dhu (2002)*, *Asten (2004)* ellipticity curves of higher modes Rayleigh waves have peaks on higher frequencies, which can be related with the second peak on H/V curve. However, another interpretation comes from simulations *Bonnefoy-Claudet (2004)* that explain higher frequency peaks as related to the resonance of body waves.

Rivet et al. (2015) compared H/V spectral ratio, computed from coda data recorded in Valley of Mexico, with theoretical ratios for various models and shows that for this site the first higher mode of Rayleigh waves is dominant. *Shapiro et al. (2001)* came to the same conclusion and according to paper of *Savage et al. (2013)* higher modes dominate also in Canterbury region of New Zealand. Fundamental mode of surface waves was found to predominate in Kanto region (*Denolle et al., 2014*).

The influence of the site's geological conditions on predomination of fundamental or higher mode of Rayleigh waves in seismic noise wavefield needs further investigation.

To sum up previously mentioned results, we can see that often used implicit assumption, according to which seismic noise wavefield consists of fundamental mode of Rayleigh waves only, is not fulfilled in general. Content of Love waves in noise can be significant, about 50%, and the particular proportion of individual waves strongly depends on the site conditions and on the noise source properties.

1.1.2.2 Noise as a diffuse wavefield

In this section, we focus on at present very popular concept - noise as diffuse wavefield. Among first authors who showed how information about Earth's crust and the upper mantle can be acquired from the seismic noise have been *Shapiro & Campillo (2004)*, *Shapiro et al. (2005)* and *Sabra et al. (2005)*. In paper *Tiggelen (2003)* are described theoretical basics. Tiggelen shows that correlation of diffuse waves can be used to retrieve wave information between two points in space-time.

In contrast to ballistic waves, which depend on source and sample just some directions, diffuse wavefield waves have random amplitudes and phases and propagate in all possible directions. According to *Weaver (1982)* diffuse field is possible to define in two ways: (1) Diffuse field at the given frequency is a state of excitation, for which the energy is evenly distributed between all normal modes. (2) Diffuse field can be represented, at each point of vibrating medium, by isotropic and random superposition of plane waves, while each plane wave has amplitude slowly fluctuating in time and random phase. In result, different plane waves and different displacement components are non-correlated.

Noise as diffuse wavefield contains all types of elastic waves and is essential, that there is connection between diffuse fields and Green's function (*Campillo & Paul, 2003; Weaver & Lobkis, 2004; Sánchez-Sesma & Campillo, 2006; Sanchez-Sesma et al., 2008; Yokoi & Margaryan, 2008*), that denotes proportion between imaginary part of Green's function at the source and average energy densities of a diffuse field (*Sánchez-Sesma et al., 2008; Perton et al., 2009*).

In case of diffuse seismic noise wavefield time cross-correlation function of diffuse seismic noise computed between a pair of distant stations allows us to obtain, at least partially, the actual Green's function between two stations. For diffuse field average autocorrelation of motion for a given direction at a given point corresponds to the energy radiated into the medium by unit load in the same direction, which can be represented by the imaginary part of GF at the observed location x for a given direction i , as $Im[G_{ii}(x, x; \omega)]$.

According to *Sánchez-Sesma et al. (2008)* within a 3D diffuse equipartitioned field, the average cross correlations of displacement between two points $\mathbf{x}_A$ and $\mathbf{x}_B$ can be written as

$$\langle u_i(x_A, \omega) u_j^*(x_B, \omega) \rangle = -2\pi E_S k^{-3} Im[G_{ij}(x_A, x_B, \omega)], \quad (1)$$

where x_A and x_B are position vectors, u_i is displacement in direction i , ω is circular frequency, asterisk $*$ marks the complex conjugate, angular brackets represent the azimuthal average, $k = \omega/\beta$ is the wavenumber of S waves, $E_S = \rho\omega^2 S^2$ is the energy density of S waves, β is the S -wave velocity and S^2 is the average spectral density of S -wave. Green's function $G_{ij}(x_A, x_B, \omega)$ gives the displacement at x_A in direction i produced by a unit load applied at x_B in direction j . For obtaining the theoretical energy density at a given point x_A we rewrite equation (1) assuming $x_A = x_B$ and we get:

$$\begin{aligned} E(x_A) &= \rho\omega^2 \langle u_m(x_A) u_m^*(x_A) \rangle \\ &= -2\pi\mu E_S k^{-1} Im[G_{mm}(x_A, x_B)] . \end{aligned} \quad (2)$$

This relationship implies energy equipartition of the 3D wavefield in space for a distribution of random sources. This provides a possibility of retrieving the propagation properties of the seismic wavefield along the ray without active seismic source. Relationship between deterministic results and diffuse fields has been clearly established by *Sánchez-Sesma et al. (2011)*.

The diffusivity is in nature created by three ways: (1) by multiple scattering in a finite body with an irregular bounding surface, (2) multiple scattering between randomly distributed scatterers within the body, (3) or due to a random distribution of uncorrelated sources distributed throughout the medium (*Pilz and Parolai, 2014*). Seismic noise is assumed to be diffuse mainly because of the distribution of sources at the surface of the Earth (e.g *Lobkis & Weaver, 2001; Derode et al., 2003; van Tiggelen, 2003; Snieder, 2004*). Seismic noise

recorded over sufficiently long time can be seen as a purely stochastic and therefore as diffusive (e.g. *Shapiro & Campillo, 2004; Shapiro et al., 2005; Yao et al., 2006*). Otherwise, it has been suggested that seismic noise wavefield does not seem to be diffuse (*Mulargia, 2012*). Authors argue that observed microtremors do not exhibit total isotropy on the horizontal plane. But it was recently showed by *Matsushima et al. (2014)* that anisotropy of observed seismic noise does not necessarily indicate violation of the diffuse field assumption in general.

Pilz and Parolai (2014) studied noise wavefield features statistically. They found that for very short duration, under 0.1 s, seismic noise shows highly ballistic nature but for longer duration, above 0.1 s, seismic noise shows just a weakly ballistic nature with diffusive characteristics.

Concept of seismic noise diffuse field nowadays has many applications. Diffuse field theory also provides theoretical explanation of H/V spectral ratio (see in more detail in section 3).

1.2 Local geological structure inferred from seismic noise analysis

In this section we briefly discuss effects of local geological structure (LGS) on the seismic noise wavefield and we also provide an overview of the basic methods that can be applied to the noise recordings with the aim to retrieve information about LGS.

1.2.1 Effect of local geological structure on seismic wavefield

An intuitive consideration that the amplitude of oscillating motion caused by an earthquake should decrease with the increasing distance from the fault, is relevant only in the case that seismic waves are propagated through the homogeneous half-space. This is, however, mainly theoretical example that occurs only rarely in the nature. More often seismic waves are propagated through very complicated structures composed of various layers and this can significantly affect amplitudes and duration of earthquake ground motion (GM) at the surface, in particular in the case of sedimentary sites with the large impedance contrasts. These effects caused by LGS are denoted as site effects.

The site effect of the earthquake is an anomaly of seismic GM, when the amplitudes of GM (at least at some frequency) and the duration of earthquake GM are inadequate to radiation characteristics of earthquake source and also inadequate to the distance from the source. Anomalous amplification at the specific frequency can be created for example, by resonance of seismic waves in the sedimentary basin. Site effect are often responsible for the biggest damages after earthquakes, because the urban areas, unfortunately, are very often built on the top of soft sediments and in close proximity to the source zone. This fact emphasizes the need for thorough study of LGS and for reliable assessment of site effects.

Moreover, if the natural frequency of buildings and of other constructions is similar to the natural frequency of the local geological structure then the mutual resonance occurs, and this phenomenon further increases damages caused by earthquakes. Frequencies larger than 1 Hz match natural frequencies of the majority common buildings. These higher frequencies are usually amplified by thin sedimentary layers. Frequencies smaller than 1 Hz correspond to the natural frequencies of long bridges and tall buildings and are amplified by thick sediment layers with thickness above 100 meters. Frequency range of engineering interest is 0.1 – 20 Hz (*Bindi et al., 2009*). So damages are dependent also on mutual interaction of subsoil and construction and this should be reflected in construction of buildings. For the purpose of complex assessment of seismic hazard it is important to know where and which kind of site effects will occur in case of possible earthquake and therefore it is necessary to obtain as much as possible information about properties of LGS.

To know the properties of LGS in sufficient detail is also important for the improvement of the knowledge of the seismic regime of a source zone (where and how often earthquakes occur). This kind of information is also another basic input into the seismic hazard evaluation.

Kanai (1954) in Japan was one from the first authors who studied connection between seismic noise and local geological structure. In recent years among others methods of analysis, methods based on seismic noise analysis becoming more popular and widely used for obtaining some information about site response.

1.2.2 Overview of seismic noise analysis methods

Problem of identification of characteristics of site responses, resonance frequencies and amplification factor, for sedimentary structure was studied for a long time by engineers and scientists and many of techniques were developed. Three different approaches for LGS investigation exist.

The first is based on use classical geophysical and geotechnical tools in connection with numerical simulations of the seismic motion (*Panza et al., 2001*). However it is complicated to use classical geophysical tools in urbanized areas because of ecological reasons and also they are costly.

The second approach is based on direct measuring of site response from earthquakes recordings from carefully located seismic station. This technique provides an unbiased estimation of site transfer amplification factor, but it is difficult to apply for sites with moderate and low seismicity.

The third and last category of the methods is based on the analysis of seismic noise recordings. This approach is attractive because of several reasons. As opposite to the conventional seismic stations, seismic noise measurement can be performed also in noisy urban environment and they provide much large data set then that of the available earthquake records. In contrary to active survey techniques these noise methods are non-invasive, i.e. does not have negative influence on environment. Moreover, they are much cheaper to perform. This group of methods is further discussed in following subsections.

1.2.2.1 Array methods

Since their development in the 1960s, seismic arrays have given a new impulse to seismology. They were originally built to detect nuclear explosions and were modified to apply on seismic noise recordings. Arrays represent many uniform seismometers in a well-defined, closely spaced configuration and produce high-quality and homogeneous data sets, which can be used to study the Earth's structure in great detail.

For this purpose many different, specialized array techniques have been developed and applied to an increasing number of high-quality array data sets. Some of them deal only with vertical space component, from which information only about Rayleigh waves can be

obtained but they are easier for interpretation. Also methods which used 3 components were developed, they give us information about Rayleigh and Love wavefield.

In further text we will describe some basics of array methods used for seismic noise analysis.

Frequency - wavenumber analysis (f-k) is beamforming method which was proposed by *Capon et al. (1967)*. Is used for obtaining the phase velocity dispersion curves for seismic noise recordings. Frequency-wavenumber method has two forms: Classical (CVFK) or High Resolution frequency-wavenumber (HRFK) method.

CVFK (Conventional FK method) is able to infer simultaneously backazimuth and horizontal slowness of seismic noise. The basic idea of CVFK processing consists of delaying the observed recordings at different stations according to a particular horizontal wavenumber vector $\vec{k} = (k_x, k_y)^T$ and computing the so-called semblance coefficient $Semb(\omega, \vec{k})$ and/or beam power $BP(\omega, \vec{k})$ of the shifted stacked output of all array stations. The beampower or semblance measure the power/coherence of a plane wave propagating with wavenumber vector $\vec{k}$. By testing many wavenumber vectors in the wavenumber plane one tries to find those wavenumber vectors which maximize the array output. The wavenumber found corresponds to a plane wave along the surface crossing the seismometer array. The main disadvantage of CVFK method is that it can be applied only to short time windows, because large time windows may contain several different phases with different slowness vectors, which makes the unambiguous identification of phase impossible (*Rost & Thomas, 2002*).

HRFK (Capon's method) is one of the most popular frequency wavenumber method applied on seismic noise. *Capon (1969)* added weighting factors (in CVFK method weighting factors equal one) to each sensor contribution in the computation of the array output in order to minimize the energy carried by wavenumbers differing from considered one. The HRFK method is theoretically able to distinguish two waves travelling at close wavenumbers in a better way than CVFK.

Spatial autocorrelation (SPAC) methods are based on the random distribution of seismic noise sources in time and space to link auto-correlation ratios to phase velocities. In the case of a single-valued phase velocity per frequency band, *Aki (1957)* demonstrated that these ratios have the shape of Bessel functions of order 0, the argument of which is dependent upon the dispersion curve values and array aperture. Application of SPAC method required perfect configuration of seismometers, which may cause difficulties, mainly in urban areas. *Bettig et al. (2001)* by modification of SPAC method create Modified Spatial Autocorrelation method (MSPAC) by which extend application of the originally method for arbitrary array configuration.

Refraction microtremor (ReMi) is method developed by *Louie (2001)* based on previously existing principles of evaluating surface waves and mainly Rayleigh waves. The most important feature is dispersive character of surface waves. The propagating waves are measured along a linear seismic array and evaluated relative to wave frequency and slowness. Due to the dispersion, higher frequency waves travel through the more shallow material and lower frequency waves travel through deeper materials. Using ReMi a 1D subsurface profile can be created based on the velocity with depth.

1.1.1.1 Cross-correlation method

The cross correlation method of seismic noise has become popular in seismology since paper by *Campillo & Paul (2003)*. The main idea is based on diffuse seismic noise wavefield when averaged over long time series. In this case, cross-correlation between the two stations yields the Green's function between these two stations. From cross-correlation process is extracted mainly the surface wave part of Green's function (*Gouedard, 2008*).

1.2.2.2 Site to reference spectral ratios

This method compares spectral ratio computed from seismic noise recording from station on site of interest with recordings from a reference site, which should be chosen as a rock or very stiff site (*Lermo & Chavez-Garcia, 1994*). Distance of both seismic stations from sources are so far that we can neglect distance between stations. So we assume the same travel distance of waves from sources to the both seismic stations. Moreover, is implicitly

assumed that there is some incoming noise wavefield and this common component may be considered as spatially uniform at least within the measurement area. Using Site to reference spectral ratio method one can obtain resonance frequency of the sediment layer and also amplification at the frequency, what is important advantages of this method. However, to find required configuration of seismometers is very difficult and in the some cases impossible.

1.2.2.3 H/V spectral ratio method

The idea of looking at the single station spectral ratio between the horizontal and vertical components was first introduced by *Nogoshi and Igarashi (1971)*. Latter it was by *Nakamura (1989)*, who merits for popularization of this method. The spectral ratio of horizontal to vertical component of seismic noise usually shows a peak which indicates the fundamental frequency of investigated site, however, based on the current knowledge, the amplitude of the H/V peak is not possible to interpret in the meaning of amplification at this frequency. Although this method is computationally relatively simple, correct interpretation of the results requires good knowledge of the properties of the noise wavefield under different circumstances together with good knowledge of experimental conditions that can have influence on the results. The advantages of the H/V method (non-invasiveness, it can applied also in noisy urban environment, financial requirements are lowest and the equipment requirements are simplest from the all noise analysis methods) together with availability of noise recordings from the permanent seismic stations in the Malé Karpaty source zone make this method a proper tool for a first survey of this source zone using seismic noise. In the past, the H/V method was applied in Slovakia in a smaller scale in the vicinity of the NPP Jaslovske Bohunice only, in order to check properties and the lateral variability of LGS (*Kristek et al., 2013*).

The H/V method is described in more detail in the Section 3 and the current knowledge of the seismic velocity model for the Malé Karpaty source zone is briefly summarized in the next section (1.3) together with information about permanent seismic stations in the area.

1.3 Malé Karpaty source zone: seismic monitoring and current knowledge of the seismic model

Source zone Malé Karpaty has been one from the most active source zones of 20th century on the area of Slovakia. Earthquake, which occurred the January 9, 1996 in Dobrá Voda is actually the biggest macroseismically observed earthquake in Slovakia, with epicentral intensity 8-9° MSK-64 (*Kárník, 1968; Zsíros, 2005*), effects of Dobrá Voda earthquake are described by *Réthly (1907)*. The Malé Karpaty area is situated in the transition zone between the Eastern Alps and the Western Carpathians (*Šefara et al., 1998; Lenhardt et al., 2007*), between the Pieniny Klippen Belt in the west and the Danube Basin in the east. This source zone is also the closest source zone to the nuclear power station Jaslovské Bohunice, so seismic activity of the source zone has big influence on the seismic hazard assessment in this locality.

At present is source zone monitored by two seismic networks, the National seismic network, which has two seismic stations in the Malé Karpaty, is the oldest seismic network in Slovakia (first seismic station in 1902) and is operated by Earth Science Institute of Slovak Academy of Sciences in Bratislava. Also three new seismic stations have been added since 2012 in cooperation of Earth Science Institute of Slovak Academy of Sciences in Bratislava with company Progseis and Institute of Rock Structure and Mechanics of the Czech Academy of Sciences. Moreover is monitored by the Local seismic network which consists from eleven seismic stations. The local network has monitored seismic activity since 1985 and it is operated by company Progseis. So currently, the source zone Malé Karpaty is monitored by sixteen seismic stations (see *Fig. 1a*).

For source zone Malé Karpaty exists currently used 3D velocity model *Geofyzika Brno (1985)*, in which are defined velocities of P-waves in the discrete points. This original model does not cover whole territory. Therefore it was extrapolated to south and west directions. Extrapolation was done according available information about geological structure of Malé Karpaty source zone by *M. Gális* (Image of extrapolated model for P-waves velocities in depth $h = 0$ is shown in *Fig.2a*).

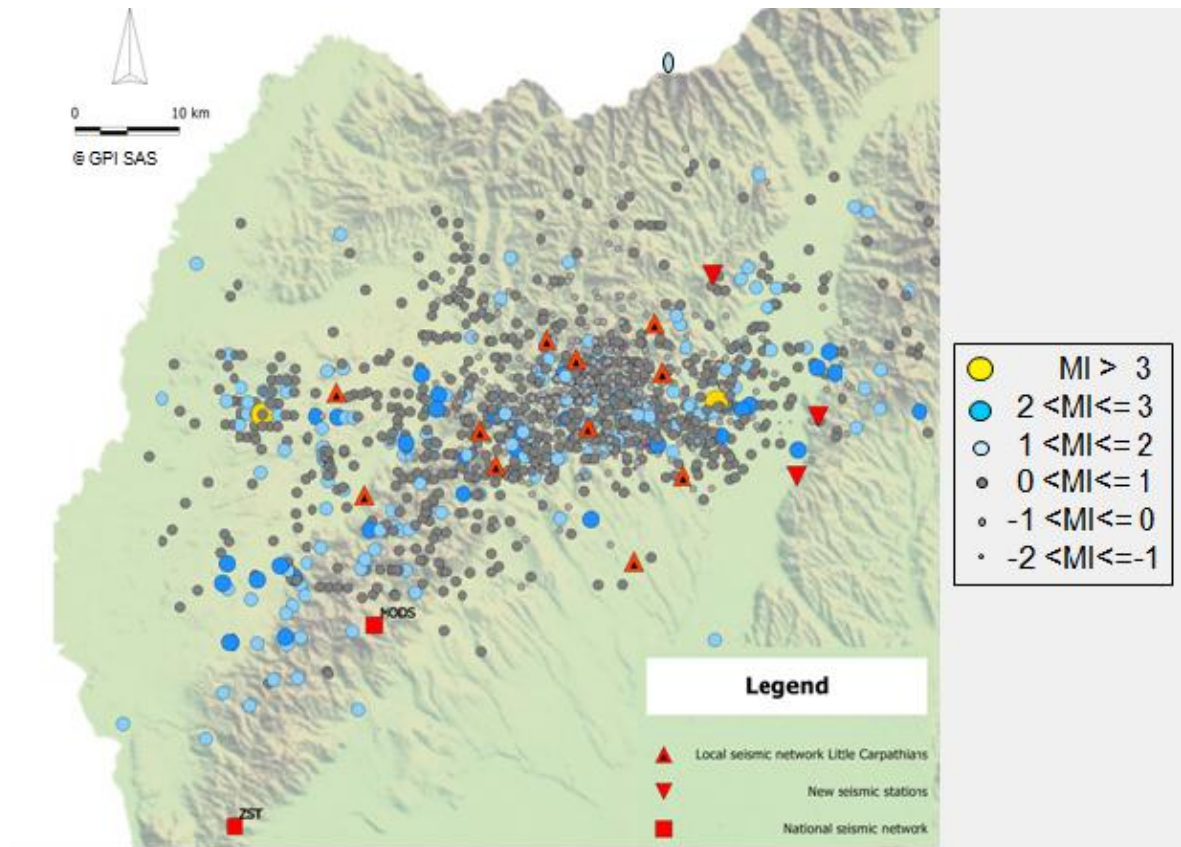


Fig. 1a. Seismic activity in source zone Little Carpathians for the period 3/1987 – 3/2013; Red triangles with point match seismic station of Local seismic network, red triangles without point match three new seismic stations operated from 2012, red squares match seismic stations of National seismic network and circles match epicentres of earthquakes with local magnitude according to legend in figure (Fojtíková *et al.*, 2013).

This model can be divided on three main parts. In the middle of the area is in direction from northeast to southwest present mountain Malé Karpaty, with high P-waves velocities, which are in range 4000 – 6200 m/s. Mountain is surrounded from northwest by lowland Záhorská nížina and from southeast by lowland Poddunajská nížina, where P-waves velocities decreases to 2000 m/s and lower. Moreover, this model is not sufficiently accurate, what was also confirmed by investigation during 7FP EU project AIM among others by Fojtíková *et al.* (2011). Also simplified 1D velocity models was published by Fojtíková *et al.* (2010) for the purpose to identify focal mechanisms of micro-earthquakes in Malé Karpaty and slightly modified 1D model was used in Fojtíková *et al.* (2016) in order to quantify capability of a local seismic network in terms of locations and focal mechanism solutions of weak earthquakes. 1D velocity models from both studies come out from existing 3D velocity model Geofyzika Brno. Seismic model was investigated and modified by smoothing also by Bulant (2010) and Jechumtálová & Bulant (2013) in order to calculate Green functions for moment tensor inversion.

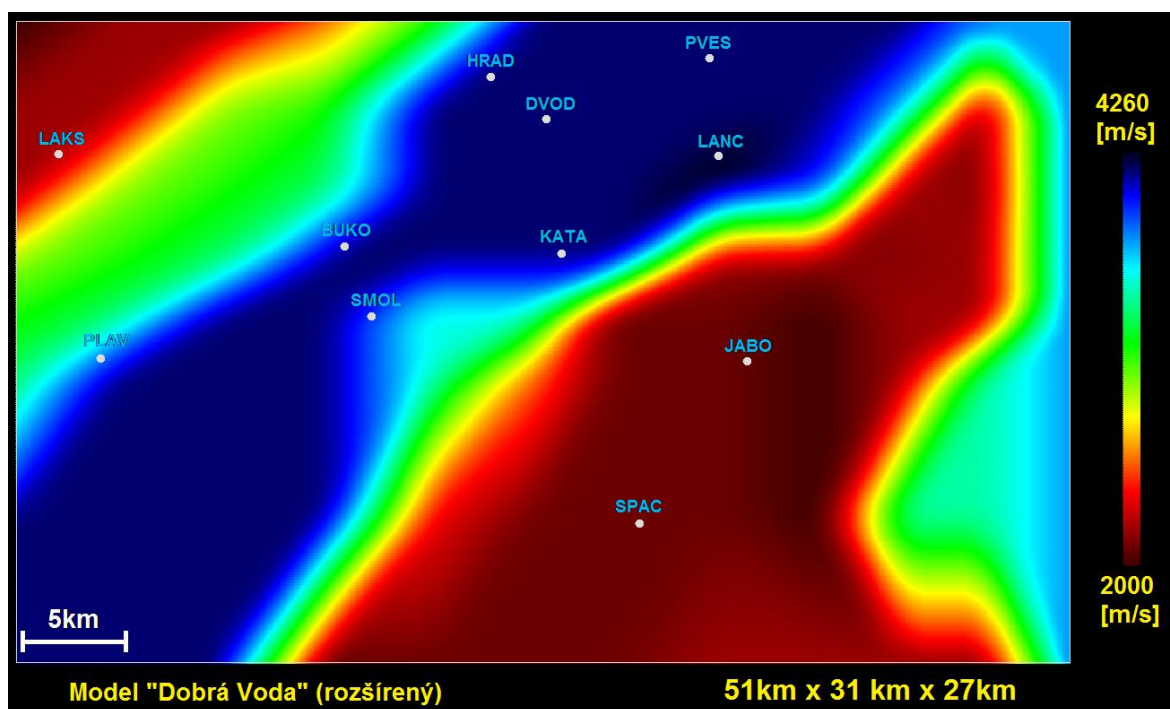


Fig.2a: Image of extrapolated P-waves velocity model of Malé Karpaty source zone in depth $h = 0$ m. Colour match P-waves velocities and points denote seismic stations (Kubina, 2011).

2 Aims of the Thesis

The main aims of the presented work are following:

- to analyse seismic noise recorded at the permanent seismic stations of local seismic network Malé Karpaty using the H/V spectral ratio method,
- to compare the obtained results with theoretical ellipticity curves and SH transfer functions, computed for the currently used seismic model of the area,
- to analyse and discuss the nature of the differences in terms of validity of the seismic model of the area.

In order to fulfil the above three main tasks another complementary subtasks should be solved

- to investigate all year variability of spectral content of seismic noise and of H/V results at the selected seismic station
- to compare results obtained by common way of H/V spectral ratio with those obtained by the computation according to *Albarelllo & Lunedei (2013)*
- to identify and exclude the peaks of artificial origin in the obtained H/V results
- to calculate ellipticity curves and SH transfer functions for currently used seismic model of source zone Malé Karpaty

3 Methodology

Single station method of H/V spectral ratio (horizontal to vertical spectral ratio), sometimes denoted as Nakamura's method, was first introduced by Japanese seismologists *Nogoshi & Igarashi (1971)* based on study of *Kanai & Tanaka (1961)*. Later, Nakamura (1989) brought the method again to the attention and since that time many seismologists have applied H/V method, reliability of which has been studied mainly experimentally and in some papers also numerically (e.g. *Lermo and Chávez-García, 1994*).

Seismic noise measurements for the H/V method can be performed using just one seismic station and therefore this method presents relatively cheap tool. It was shown, that H/V method can be used for the estimation of the fundamental frequency of the sediment site. The best results can be obtained in the case of big impedance contrast between soil layers. Although computation of H/V spectral ratio is a relatively simple, the proper measurement conditions together with selection of the parameters of computation are very important and the interpretation of the results can be complicated in some cases.

The simplicity of the computation together with low cost equipment and non-invasiveness makes the H/V method appealing to apply and many times the method was used like a "black box", what led to too strong or misrepresented conclusions. International FP5 EU project SESAME was devoted to the important issue of site effect estimation for seismic risk mitigation, with special attention to urban areas. It was focused on two low cost techniques using ambient seismic vibrations (the H/V method and the noise array measurements). SESAME project significantly contributed to clarification of the actual ability of the above methods to provide useful, direct or indirect, information for local amplification estimates. The work included a theoretical and numerical part to better understand the nature of seismic noise, and to develop validated numerical tools to simulate seismic noise in arbitrary environments. It also included thorough experimental and data processing investigations to clearly assess the stability, robustness, reliability and physical meaning of these 2 techniques. Using many tests on real data and numerical simulations recommendations were elaborated. They are summarized in the two deliverables: Deliverable D23.12 „Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations. Measurements, processing and interpretation“ (SESAME Deliverable D23.12, 2004) and Deliverable D08.02 „Final report on Measurement

Guidelines. H/V technique: experimental conditions“ (*SESAME Deliverable D08.02*, 2003). Both the guidelines are widely used and can serve as very useful source of information up to now for anyone using the H/V method.

If H/V curve shows significant peak, which has not artificial origin and satisfies criteria of reliability and significance, then peak indicates presence of site effect with possible anomalous amplification of seismic motion during earthquake at given frequency. The local geological structure then probably contains an interface with quite sharp velocity contrast. Frequency of significant peak on H/V curve should correspond to resonance frequency of local geological structure. For a layer over the halfspace, the resonance frequency is proportional to S- wave velocity in the layer and inversely proportional to the thickness of the sediment layer, according to

$$F_n = \frac{(2n + 1)v_s}{4h} \quad (3)$$

Another possible interpretation of H/V peak is related to the presence of the surface Railegh waves in the noise field and to their ellipticity. Considering the current knowledge, in general, it is not possible to interpret amplitude of H/V peak in terms of amplification of seismic motion caused by local effect of earthquake. However, another option that peak of the H/V ratio can be explained with vertical incident SH wave only and thus shows amplification characteristics by the multiple reflections of the SH wave is presented mainly by *Nakamura (1989)* and his followers.

In further text we describe the principle and properties of the H/V method in more details.

3.1 Computational principle of H/V spectral ratio

Three spatial components of seismic noise are needed for computation of H/V spectral ratio. The computation of H/V spectral ratio is realized in following basic steps:

- 1 In the first step, every single component (i.e. vertical, east-west and north-south) is analysed in the time domain. The seismic noise recording is divided into time windows with appropriate length and time windows which contain transient signals are visually identified and excluded from further analysis.

- 2 Signal in the time domain is divided into time windows with proper length (see 3.3.2) Seismic noise recording has to be long enough to be divided on sufficiently amount of non-overlapping time windows. In the next, every single time window is processed separately.

Simple cutting of seismic noise recordings is equivalent to using a rectangular window and this is not suitable for spectral analysis. Therefore, 5% long cosine window at the both sides of analysed time window is usually applied to all three components.

Then the Fast Fourier transformation is performed on all three components of seismic noise recordings of given time window and three amplitude spectra are obtained as the result.

- 3 The ratio of the two merged amplitude spectra of horizontal and of one vertical component is computed for every time window separately.

Horizontal components can be merged by several ways, where H denotes average amplitude spectrum as a function of two horizontal components, H_N amplitude spectrum of North-West horizontal component and H_E amplitude spectrum of East-West horizontal component:

- a. Quadratic mean, $H = \sqrt{H_N^2 + H_E^2}/2$, used by Bonnefoy-Claudet et al. (2006, 2008). This way of merging is also implemented in the software Geopsy that we use in this thesis.
- b. Geometric mean, $H = \sqrt{H_N \cdot H_E}$, used by Picozzi et al. (2005) and recommended by SESAME project (2004).
- c. Arithmetic mean, $H = (H_N + H_E)/2$, used by Chavez-Garcia et al. (2007).
- d. Vector summation, $H = \sqrt{H_N^2 + H_E^2}$, used by Sauriau et al. (2007).
- e. Maximum horizontal value, $H \equiv \{H_N, H_E\}$, used by Konno & Ohmachi (1998).
- f. No combination, components H_N , H_E are considered separately, two H/V curves are computed, as used in Lermo & Chavez-Garcia (1994).

- 4 Application of smoothing procedure of spectra is highly recommended. Because raw generally show lot of very narrow oscillations and spikes which alter their

readability. Moreover, this could lead to large numerical errors when computing the H/V ratio using such spiky spectra. Before computing H/V, smoothing is applied to the Fourier spectra amplitudes of the three components. Several types of smoothing functions exist, the most suitable is Konno & Ohmachi smoothing function (Konno & Ohmachi, 1998):

$$\frac{\sin\left(\left(\log_{10}(f/f_c)\right)^b\right)}{\left(\left(\log_{10}(f/f_c)\right)^b\right)^4}, \quad (4)$$

where f is the frequency, f_c is the central frequency where the smoothing is performed and b is the bandwidth coefficient. The constant bandwidth on a logarithmic scale is used in this smoothing procedure. A small value of b leads to a strong smoothing and a large value of b leads to a weak smoothing of the Fourier spectra.

Another types of smoothing functions are e.g. constant and proportional. Constant smoothing has a triangular shape centred on the current frequency and its width is equal to “band width”. And proportional has also triangular shape but width depends on the current frequency.

- 5 Finally, the resulting H/V ratio is estimated by geometric average of H/V spectral ratios computed for n individual time windows:

$$H/V_{average} = \frac{\sum \log_{10}(H/V)}{n} \quad (5)$$

And standard deviation is given as:

$$\sigma_{H/V} = \sqrt{\frac{\sum \log_{10}^2 - n \times \log_{10}^2(H/V_{average})}{(n-1)}} \quad (6)$$

$H/V_{average}$ and $\sigma_{H/V}$ can be calculated to a linear scale like $\overline{H/V} = 10^{H/V_{average}}$ and $\sigma_{\overline{H/V}} = 10^{\sigma_{H/V}}$ (SESAME Deliverable D08.02, 2003).

The alternative way of computation was proposed by *Albarelli & Lunedei (2013)*. H/V spectral ratio is computed as the squared root of the ratio of average horizontal and vertical ground motion power spectra, each separately computed from a large set of non-overlapping time-windows extracted from the original recordings.

$$H/V_{average} = \sqrt{\frac{\overline{H^2}}{\overline{V^2}}} \quad (7)$$

In the paper authors investigate influence of procedure used for merging horizontals on the resulting H/V. They compare “traditional” way of H/V computation (see eq. 5), i.e. H/V result is obtained by arithmetical averaging H/V spectral ratios computed over a number of time-windows with H/V spectral ratio computation proposed by them. They claim, that in the case of computation of H/V according to equation (7), resulting H/V is less biased for all merging procedure (except of case of maximal horizontal values characterized by different convergence behaviour) and also a role of smoothing is smaller. But is needed to emphasize that in this study just one experimental example was done, so further analysis is needed.

3.2 Theoretical explanation of H/V spectral ratio

An interpretation and a reliability of the H/V spectral ratio are closely related to the composition of the seismic noise wavefield, which is depend on the sources and local geological structure as we already described in more details in section 1.1.2. Seismic noise wavefield consists of different types of seismic waves, which can have different effects on the H/V spectral ratio: Rayleigh wave ellipticity, Airy phase of Love wave modes, and resonance of body waves.

Effects of different wave types contained in noise wavefield on H/V ratio

In case of *Rayleigh waves*, their particle motion is characterized by retrograde elliptical motion in radial plane, which is in the some depth changed to prograde. In case of horizontally stratified media, particle motion and also phase velocity are frequency dependent. As a consequence of stratification distinct Rayleigh wave modes exist, while

fundamental Rayleigh mode is the only mode which exist at all frequencies. The H/V ratio of Rayleigh waves exhibits frequency dependence in a stratified media.

Considering H/V ratio from Rayleigh waves only and in the case of one simple layer over half-space we can summarize following results according to e.g. *Bard (1999)*, *Stephenson (2003)*, *Bonnefoy-Claudet (2004)*, *SESAME Deliverable D23.12 (2004)* and others. For S-wave velocity contrasts larger than value about 3, H/V from ellipticity of Rayleigh waves exhibits infinite peaks and/or zeros, which correspond to the vanishing of the vertical or horizontal components. For velocity contrast above value of 4, in the case of fundamental mode, the vanishing of the vertical component occurs at the frequency f_R which is close to the fundamental resonance frequency for S waves. For intermediate contrasts, 2.6 – 4, ellipticity peak occurs at the frequency up to 50% higher than S wave fundamental resonance frequency. And for a low velocity contrasts, the infinite peak is replaced by broad maximum with low amplitude at the frequency that differs from S-wave fundamental frequency 0.5 to 1.5 times. H/V ratio of fundamental mode of Rayleigh waves can besides peak at frequency f_R exhibits also minimum (zero) at a higher frequency f_Z , both possibilities are due to vanishing of horizontal component. For higher modes, H/V curve exhibit also peaks at the higher frequencies corresponding to a vanishing of V component. For high contrast structures, some of these peaks agree with higher harmonics of S-wave resonance.

Love waves are polarized only in the horizontal plane, so they can affect only horizontal component of the H/V ratio. According *Konno & Ohmachi (1998)*, Love waves do strengthen the H/V peak, at least in case of high impedance contrasts. Surface waves carry their maximum energy for frequencies corresponding to group velocity minima, so called Airy phase. In the case of high impedance contrasts Airy phase occurs at a frequency f_L that is close to the fundamental S-wave resonance frequency. Group velocity minima of higher modes of Love waves can cause other maxima on H/V curve if higher modes have enough energy.

In case of *body waves*, considering a simple horizontally layered structure with large impedance contrast, one soft layer over a half-space and obliquely incident plane waves, the horizontal components always exhibit resonant peaks at the S-wave resonance frequency, no matter what wave type of incident wave. And the vertical component always exhibits resonant peak at the P-wave resonance frequencies. Fact that P-wave fundamental

frequency is considerably higher than the S-wave fundamental frequency has several consequences for the fundamental mode: (1) Subsurface topography has just weak influence on the fundamental frequency, what explains why H/V spectral ratio for a body waves, in case of high impedance contrast, should always show a peak around the fundamental S-wave frequency. (2) For a horizontally layered structure, at least for peaks which do not agree with a lower order harmonic of P-wave resonance, the H/V should have peaks also at the S-wave harmonics. (3) In case of high impedance contrast and horizontally stratified structure, the amplitude of the first H/V peak should be correlated with S wave amplification. Point (2) and (3) are the main differences between body and surface waves cases (*SESAME Deliverable D23.12, 2004*).

Conclusions from numerical simulations

Since, in general, the composition of seismic noise wavefield is unknown, the numerical simulations have been performed in order to investigate influence of the different wave types on the H/V curve (*Bonnefoy-Claudet, 2004; Bonnefoy-Claudet et al., 2006, 2008*).

Bonnefoy-Claudet et al. (2006) conclude from 1D noise simulations for one sedimentary layer over a bedrock characterized by high impedance contrast : (1) H/V exhibit one single peak due to resonance of Rayleigh waves, in case of near and surficial source. (2) H/V curve exhibits two peaks, first peak is due to two effects, fundamental Rayleigh waves resonance and resonance head S waves and second only due to resonance of head S waves, in case sources are located within sedimentary structure and far away. (3) H/V ratio shows peaks at the fundamental and harmonic resonance frequencies, in case deep sources within bedrock. In this case only non-dispersive body waves are present in noise wavefield, thus H/V is due to multiple reflections of S waves inside the layer.

However, in case of recordings of real noise from a site, all types of sources can be acting in the same time. It is observed in this case, that H/V curve the most often exhibits only one peak. Thus H/V ratio is controlled mainly by local surface sources, or mainly due to ellipticity of the fundamental Rayleigh waves. And thus amplitude of H/V peak does not give good estimate of site amplification factor. The amplitude of H/V spectral ratio overestimates or underestimates the site amplification factor (e.g., *Bonnefoy-Claudet et al., 2008; Haghshenas et al., 2008*). For low impedance contrasts Rayleigh wave ellipticity cannot explain the peak of H/V ratio curve. Airy phase hypothesis, that Airy phase can be

even responsible for the H/V peak is satisfied only in the case of high or medium impedance contrasts. *Bonnefoy-Claudet et al. (2008)* conclude that S-wave impedance contrast is the main parameter which controls H/V peak.

However, for 1D horizontally layered structures it was found, that H/V peak frequency, whatever the H/V peak origin is, it always provide a good estimate of the fundamental resonance frequency (Bonnefoy-Claudet, 2006, 2008).

Interpretation based on diffuse field

An alternative method to interpret H/V ratio is based on the recent diffuse field concept (*Sánchez-Sesma et al., 2008*) (described in section 1.1.2.2). Theoretical form of the H/V spectral ratio has been proposed to be equal to the square root of the ratio between the imaginary part of horizontal Green's function on the surface and that of the vertical one (*Sánchez-Sesma et al., 2011*). It links average energy densities with the Green's function in 3D. The theory assumes that energy of a wavefield inside the Earth will be equipartitioned among the various states in 3D space. In case of seismic noise, this may occur for randomly applied point-force loadings on the surface after sufficient lapse time to allow multiple scattering. This theory allows compute the H/V spectral ratio as an intrinsic property of the medium.

According to *Sánchez-Sesma et al. (2011)* assuming that seismic noise wavefield is diffuse, stabilized spectral densities can be interpreted as directional energy densities (DEDs). Then H/V spectral ratio can be expressed as:

$$[H/V](\omega) = \sqrt{\frac{E_1(x, \omega) + E_2(x, \omega)}{E_3(x, \omega)}} \quad (8)$$

Where E_1 and E_2 denote DEDs and indexes 1 and 2 match horizontal and 3 vertical degrees of freedom.

Using equations (2) and (8) according to *Sánchez-Sesma (2011)* the following relation is obtained:

$$[H/V](\omega) = \sqrt{\frac{\text{Im}[G_{11}(x, x; \omega)] + \text{Im}[G_{22}(x, x; \omega)]}{\text{Im}[G_{33}(x, x; \omega)]}} \quad (9)$$

This equation connects “average” measurements expressed on the left-hand side with an intrinsic property of the medium on the right-hand side, and naturally allows for the inversion of H/V ratio accounting for the contribution of every wave type (*Sánchez-Sesma et al., 2011*).

3.3 Influence of various parameters on H/V results

Before performing seismic noise measurements for the H/V method, it is important to know which parameters have during the recording influence on H/V results. Awareness of possible influences is also important for reliable interpretation of H/V results. During SESAME project the extensive study has been done, during which various effects of experimental condition were investigated (see SESAME project: *WP02 Controlled instrumentation specification, Final report, Deliverable D01.02, 2002; WP02 H/V technique : experimental conditions, Final report, Deliverable D08.02, 2013*) . Diploma thesis by Fojtíková (2001, in Slovak) also discussed the influence of experimental conditions on H/V spectral ratio. In general, the factors, which can affect H/V results during noise measurements, can be divided into two main categories: Influence of instrumentation, influence of experimental conditions.

3.3.1 Influence of instrumentation

According results from SESAME project, tests done with various instrumentation give us following conclusions and recommendations.

For digitizers there is some warm up time needed, from 2 to 10 minutes. It is recommended to check the energy density along the studied frequency band, whether is sufficient for extraction of the signal from the instrumental noise. Also the check of synchronisation between channels is recommended and the same gain for all three channels should be selected. It is important to keep on mind, that small gain differences might cause slight changes of the results.

From test with sensors it was found that accelerometers are not sensitive enough for frequencies lower than 1 Hz, and therefore they are not recommended for H/V seismic

noise measurements. It is not recommended to use broadband seismometers because they require long stabilization time. And also it is necessary to avoid the use of sensors which have their natural frequency below the frequency of interest. However, under certain conditions, it is possible to retrieve also H/V peak below the natural frequency of seismometer (see *Bindi et al., 2009*).

It is recommended to fix the gain level at the maximum possible without signal saturation. In general, a sampling rate higher than 50 Hz is not needed, while engineering interesting frequencies are below 25 Hz.

3.3.2 Influence of experimental conditions

In general it is recommended to check a site before H/V measurements, to have a look at available geological information and at possible sources of anthropogenic noise. This preparation step might help later, during interpretation of the results.

Influence of recording duration

It is recommended that for given frequency of interest, there should be at least 10 significant cycles in each time window, i.e. to fulfil the condition: $f_0 > 10/l_w$, where f_0 is frequency of interest and l_w is length of time window. Also a large number of windows and of cycles, over 200, is requisite. Thus for total number of significant cycles n_c the condition $n_c = l_w \cdot n_w \cdot f_0 > 200$, should be satisfied. Where n_w denotes number of time windows. For example, for a peak at 1 Hz, it is needed at least 20 windows of 10 s each.

Influence of distance between measurement points

Selection of the measurement's grid depends on purpose of measurement. Initial large spacing is recommended (about 500 meters) for a microzonation measurements and then to later densify the grid point spacing in the case of lateral variation of the results. In order to investigate single site response, at least three close measurement points should be used to derive an f_0 frequency. Deriving of f_0 frequency from only one measurement point should be avoided.

Influence of in situ soil and sensor coupling

Choice of in situ soil and sensor coupling is very important. In general concrete and asphalt give good results, while irregular or soft soils as for example grass, ice, mud and others need more careful approach. Sensor should be placed directly up on the ground, except of special cases, to achieve good coupling. Layer of asphalt or concrete does not have effect on H/V results, although some small perturbations, that do not affect shape of H/V curves, can be observed in the 7-8 Hz band. H/V results below 1 Hz can be significantly affected by recording on the grass, when wind is blowing. Therefore, before setting a sensor on the grass is better to give away high grass, respectively to dig a hole. But this is effective just when some constructions or trees which can also induce some strong perturbations at low frequencies are not present in surroundings. It is recommended to completely avoid setting the seismometer on soft superficial layers as ploughed soil and similar and also to avoid measurements on water saturated soils. Recordings should be performed only on firm surface. Snow and ice can also have effect on H/V results. In such a case, it is recommended to install sensor on a metal or wood plate and set on compacted snow.

In case of use of artificial interface, is recommended to perform some tests before recording.

Influence of nearby structures

As briefly mentioned above, near structures like trees, buildings can have influence on the H/V results. The movements of the structures due to the wind can set up perturbations in the ground at the low frequencies. There is not any quantitative criterion for minimum distance from structures where H/V results are not affected. It is highly advised to avoid of recording on underground structures (car parks, sewer lids etc.) since these structures may markedly bias the amplitude of the vertical component of the motion.

Influence of the weather conditions

It is suggested to avoid recording during windy weather, since even a slight wind (about > 5 m/s) can have big influence on the H/V curve below 1 Hz. Also heavy rain has influence on the H/V curve; on the other hand slight rain has no remarkable effect. Attention should be paid in case of extreme temperatures or low pressure meteorological events during measurement. Such events can alter the H/V results, since they generally raise the low frequencies.

Influence of the sources of disturbances

There was not detected noticeable influence from high voltage cables on H/V results. According to the recommendations from SESAME project all kind of short-duration local sources, for example traffic, footsteps, etc., may disturb H/V curve results. It is not possible to give universal minimum distance value, since the influence of transient sources depends on various factors like energy of source and structure of the soil. In general it can be said that sources with short periods of high amplitudes as fast highway traffic, alter H/V if they are in distance smaller than 15-20 meters. Slow traffic have influences on H/V within smaller distances. Events with short duration, so called transients, can be removed during H/V analysis, but in that case it is needed to prolong the time duration of the recording. Next, is highly recommended to avoid recording in close proximity to monochromatic sources. Issue of influence of transient signal on H/V results was investigated, beside of project SESAME, e.g. also by *Parolai & Galiana-Merino (2006)*.

3.4 Interpretation of H/V results

In this section we summarize the main criteria and recommendations for interpretation of H/V results, which were acquired during SESAME project.

3.4.1 Criteria for a reliability of H/V results

Criteria for a reliability of results are divided in two following sections:

Criteria for a reliable H/V curve

Each from three following criteria should be fulfilled at once.

- a. $f_0 > 10 / l_w$, where f_0 denotes frequency of interest and l_w length of time window.
- b. $n_c(f_0) > 200$, where n_c is number of significant cycles $n_c = l_w \cdot n_w \cdot f_0$, where n_w is number of time windows selected for the average H/V. This value should be increased in case that transients are present in signal.
- c. $\sigma_A(f) < 2$ for $0.5 f_0 < f < 2 f_0$ if $f_0 > 0.5 \text{ Hz}$,
or

$$\sigma_A(f) < 3 \text{ for } 0.5 f_0 < f < 2 f_0 \text{ if } f_0 < 0.5 \text{ Hz},$$

where $\sigma_A(f)$ is standard deviation of $A_{H/V}(f)$.

Criteria for a significant H/V peak

According to the SESAME, for a clear H/V peak minimally 5 out of 6 following criteria should be fulfilled.

a. $\exists f^- \in [f_0/4, f_0] | A_{H/V}(f^-) < A_0/2$

There exists such a frequency from the interval from $f_0/4$ to f_0 that her amplitude is more than half smaller than frequency f_0 . This criterion says about the expressiveness of f_0 amplitude compared to the lower nearby frequencies.

b. $\exists f^+ \in [f_0, 4f_0] | A_{H/V}(f^+) < A_0/2$

There exists such frequency from the interval from f_0 to $4f_0$ that her amplitude is more than half smaller than frequency f_0 . This criterion says about the expressiveness of f_0 amplitude compared to the higher nearby frequencies.

c. $A_0 > 2$

Amplitude at the frequency f_0 should exceed value 2. This criterion from *SESAME (2004)* should be not applied in a too conservative way, because at the same site amplitude of f_0 frequency can vary slightly about this limit. In the case of amplitudes a little bit under value 2 observed on more than one site, additional recordings should be performed and interpreted by comparison with neighbouring sites (*Guillier et al., 2007*).

d. $f_{peak} [A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$

Peak frequency of the H/V curve plus or minus standard deviation of H/V curve should be the same frequency as f_0 with variation 5%.

e. $\sigma_f < \varepsilon(f_0)$

Standard deviation of H/V peak frequency ($f_0 \pm \sigma_f$) should be smaller than threshold value $\varepsilon(f_0)$.

f. $\sigma_A(f_0) < \theta(f_0)$

“Standard deviation” of $A_{H/V}(f)$, σ_A should be smaller than threshold value $\theta(f_0)$.

Threshold values for $\sigma_A(f_0)$ and σ_f are shown in *Table 1*.

Frequency range [Hz]	< 0.2	0.2 – 0.5	1.0 – 2.0	1.0 – 2.0	> 2.0
$\varepsilon(f_0)$ [Hz]	$0.25 f_0$	$0.20 f_0$	$0.15 f_0$	$0.10 f_0$	$0.05 f_0$
$\Theta(f_0)$ for $\sigma_A(f_0)$	3.0	2.5	2.0	1.78	1.58
$\log \Theta(f_0)$ for $\sigma_{\log H/V}(f_0)$	0.48	0.40	0.30	0.25	0.20

Table 1: Criteria for a reliable H/V curve (SESAME, D23.12, Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations, 2004)

3.4.2 Main peak types

Nature of seismic noise has some consequences for the interpretation of H/V results. It is good to be aware of the fact that the results are usually simple and clear only in the case of horizontally layered structures with impedance contrast bigger than 4-5. The results become more uncertain for increasing underground interface slopes and for decreasing contrasts. In the Rayleigh wave interpretation, the H/V peak should be associated with a local trough in the Fourier spectra of the vertical component and Love or body waves otherwise with a local peak in Fourier spectra of the horizontal component (SESAME, D23.12, Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations, 2004).

Important is also to consider possible variation of H/V during night and during day because of variation of seismic noise due to change in contribution of different noise sources related to human activities. Weekly and monthly variation of H/V has been also investigated (e.g. Hollender et al., 2011; Guillier et al., 2007). During the night, a very low level of noise was recorded within the frequency band of 2–10 Hz. This level was one to two order of magnitude lower than during the day. For urban areas with many non-natural noise sources, only H/V peaks obtained during night measurements are connected with the local geology, frequency of the peaks can be shifted between day and night (see example in the Fig.2). Therefore it is recommended to perform at least one 24 – hours measurement on the site of the interest to evaluate daily variation (Hollender et al., 2011). Guillier et al. (2011) conclude that H/V results, fundamental frequency and natural peak, are robust over time in microseism's range of frequencies.

Authors of some papers, e.g. Hollender et al. (2011), also suggest that H/V method is a useful tool to map the depth of the bedrock (see Fig.3a). Influence of lateral heterogeneity on H/V spectral ratio was studied also by Matsushima et al. (2012, 2014) using observed

and synthetic noise, by comparison of H/V ratio computed separately from east-west and north-south horizontal component, derived from Green's function. Effects of 2D/3D structures can be investigated by differences between differently polarised horizontal components (*SESAME deliverable D23.12, 2004*)

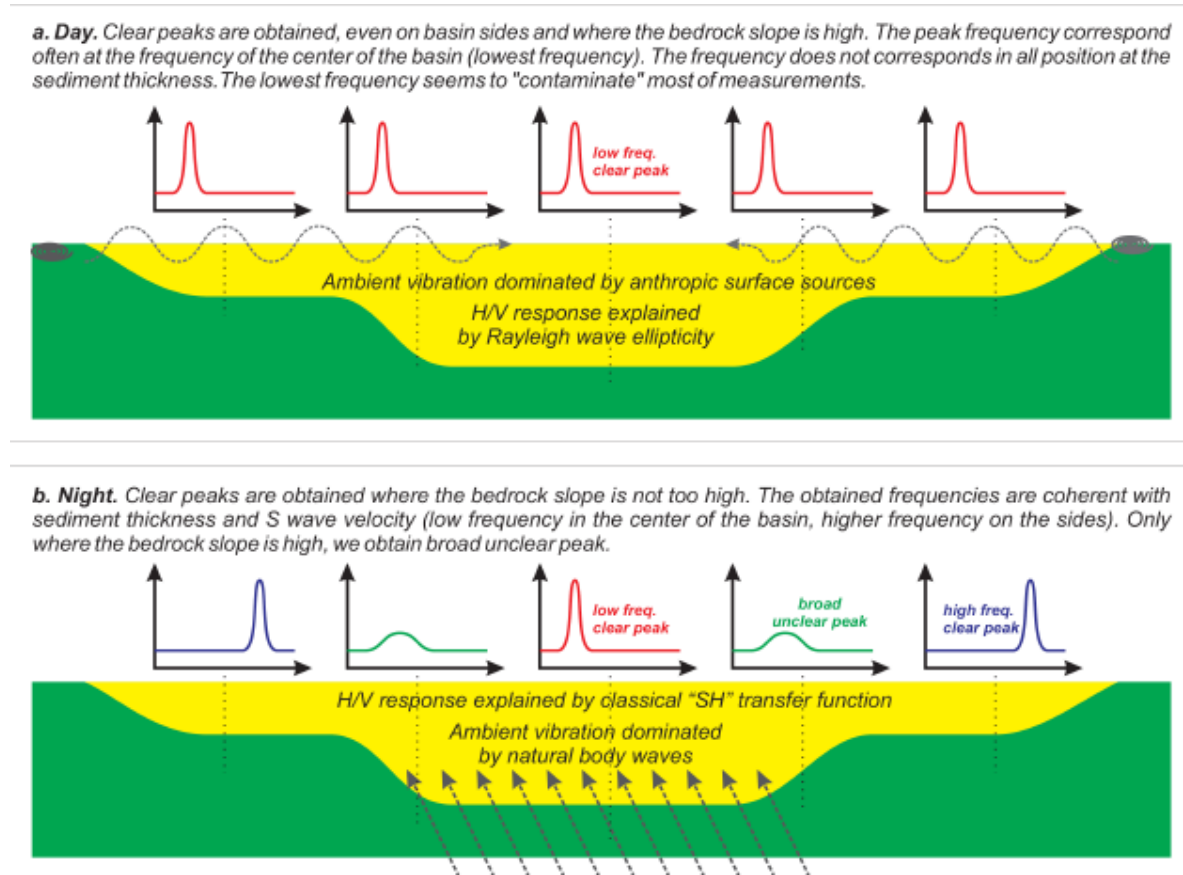


Fig. 3a. Frequency shift between day and night, multidimensional effect: explanation proposition (*Hollender et al., 2011*).

A many types of peaks can be seen on H/V results. In the following text we describe the most common situations according to the results of the SESAME project.

Sharp industrial peaks. Significant sharp peaks or troughs are often connected with human activities or with industry and are often related to monochromatic sources. In this case the frequency of the peak does not give estimate of f_0 . Indications for industrial origin of the peak are that raw spectra shows sharp peaks usually on all components, random decrement technique exhibits damping under 5%. Useful tool for identification of artificial peaks is also time-frequency analysis using continuous wavelet transform (*Kristeková, 2006; Kristek et al., 2013*).

Clear peak. If there is no indication of artificial nature of the peak and H/V curve exhibit single peak which satisfies criteria of reliability and it is significant enough compared to other peaks at neighbouring frequencies and at the same time the frequency of the peak is higher than frequency of the sensor, then the frequency of the peak is reliable. It indicates likely large contrast at the depth and represents reliable estimate of fundamental frequency.

Unclear low frequency peak. Origin of the unclear peak can be caused by many conditions, for example bad weather conditions during the measurement, low impedance contrasts or velocity gradient in the depth, bad placement of a sensor or use of improper type of the sensor. To distinguish between these options is a difficult task. In case of unclear peaks it is recommended to consider the geology of the site. E.g., to verify whether it is possible, that unclear peaks are more likely due to thick, stiff sedimentary deposits. Then to check weather conditions from the time of measurement. If value of H/V curve when frequency is close to zero is larger than 2, it may be caused by wind, traffic or bad sensor. Reprocessing of the data using longer time window is also recommended or more stringent criteria for selection of time windows in order to decrease standard deviation. Other possibility is to reprocess the data with changed smoothing parameters, with proportional bandwidth or using less smoothing. If it helps to clarify low frequency peak it is likely that this peak is linked with local geological conditions.

Broad or multiple peak. Firstly, is necessary to check if it is not artificial peak. If there are no indications of artificial origin, then it is recommended to apply weaker smoothing in case of broad peak and otherwise, in case of multiple peaks to increase smoothing and to check stability.

Two peaks case. H/V curve can exhibit also two peaks, which both satisfies criteria for the reliability (3.4.1). It was shown that in this case two large impedance contrasts probably occurred at two different scales, one for thick structure and the other for a shallow structure. The frequencies f_0 and f_1 , where f_0 is smaller than f_1 can be interpreted as characteristics at each scale. But firstly it is recommended to carefully check whether this is actually the case by reprocessing the data, check natural/artificial origin of the peaks and check information about geology.

Flat H/V curve. H/V curve does not exhibit any significant peak, amplitude values lies under 2.0. In this case it is very likely that local geological structure does not contain any large impedance contrast. But it does not necessarily mean, that there is no site amplification. However, situation that H/V exhibit flat curve for non-rocky sites is very rare, it was observed in less than 5% of studied sites within SESAME project

4 Results and discussion

4.1 Preparatory analyses and tests

In this section we present results of several additional analyses and tests that are complementary to the main results (discussed in the Sections 4.2 and next). Need to perform also these additional analyses resulted from our previous work done in the bachelor thesis (*Dufalová, 2014*) and also based on published papers relevant to the topic of this diploma thesis.

During work on bachelor thesis (*Dufalová, 2014*), investigations of the stability of the spectral content of seismic noise and of the H/V results (daily and seasonal variations) for seismic station Špačince (SPAC) have started. Seismic noise data recorded by station SPAC in 2013 were used. However, at that time, the data from autumn 2013 were not available yet, so whole year seasonal study could not be completed. As the authors of several papers already shown (see Section 3.4.2 for more details), it is important to consider possible variation of H/V during night and day, also weekly and seasonal variations due to the change in contribution of noise caused by human activities. Therefore before fulfilling the main goal of the thesis we finalized the study of all year variability of the station SPAC as the representative station from the area of interest. Results can be found in the Subsection 4.1.1.

In addition to the variability analysis we have tested another computational algorithm for estimation of H/V spectral ratio, suggested by *Albarelli & Lunedei (2013)* and compared the results with the results obtained using common way of computation. We have also tested influence of different kinds of averaging procedures for the merging of the two horizontal components. Results of this group of tests are summarized in the Subsection 4.1.2.

4.1.1 Analysis for seismic station Špačince

Seismic station Špačince (SPAC) was selected as a suitable station for tests of variability of results with time since in the area there is a lot of possible noise sources that can cause significant variability. The station is placed at the end of a village, however in close proximity of gardening areal, junkyard, of agricultural fields and also of industrial facilities. So many possible anthropogenic sources may affect seismic noise content. By detailed variability tests we can obtain valuable information about character and variability of seismic noise on locality and about the effects of anthropogenic sources on H/V results.

In the bachelor thesis (*Dufalová, 2014*) variability of noise data from station SPAC during winter, spring and summer of 2013 was investigated. Therefore within this diploma thesis we have started with the analysis of noise data from the autumn of 2013. Spectra and H/V spectral ratios were calculated for the same time periods within day and night time as it was in the case of other seasons. The autumn 2013 results were compared with results for other year's seasons from the bachelor thesis.

The H/V spectral ratios for each season of the year 2013 are displayed in *Fig. 1*. Blue curve is for noise data from 4.4.2013, green is for 28.6. 2013, red H/V is from 31.1.2013 and black is for 10.10.2013. All results in the *Fig. 1* correspond to noise recordings from working days. H/V curves calculated from daily part of noise recordings, between 09:00 to 13:00, are displayed in the figure only.

We can see from *Fig. 1* that character of H/V curve for every season at intermediate frequency range is quite stable, frequencies of the peaks do not change with time. The only exception is the peak at 1 Hz which occurs only on autumn and summer H/V curve. Its time variability and also TFA results (narrow line) strongly indicate its artificial origin and therefore it should be excluded from further analysis. Noticeable is also abnormal character of autumn's H/V curve at the lowest and highest frequencies where it is clearly different from other H/V curves.

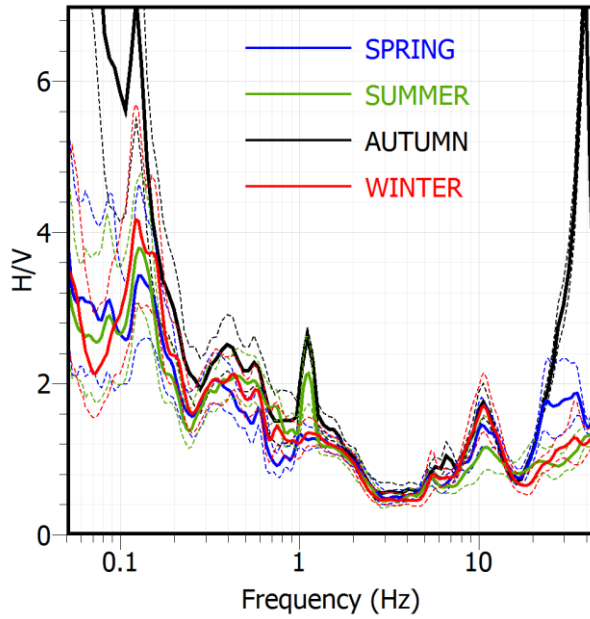


Fig. 1: Seasonal variability of H/V curves from seismic station SPAC. Solid lines are average H/V spectral ratios and dashed lines are standard deviations.

We tried to investigate in more detail this abnormally increased amplitudes of H/V at the mentioned frequencies. We have checked whether this anomaly is not specific just for the selected part of noise data (lasting for a short time only).

Short time anomaly can be due to agricultural activities on nearby fields or due to weather conditions. Other possibility was that it was something longer and characteristic for autumn season at the SPAC site. Therefore we have created time-dependent graphs of H/V as follows: every day during one week was divided into 8 four-hour long segments. For each four-hour long data segment one H/V ratio and also spectrum of each component were calculated, so one day segment in the graphs consist of 8 H/V curves or of 8 spectra. To this purpose we have used, in a modified way, the tool in software Geopsy originally developed for creation of spatially dependent graphs. Using this kind of graphs we can see in more detail variability of spectral content and of H/V ratio results during one week. Time-dependent graphs are also useful tool for identification of cultural contributions to seismic noise wavefield as they help us to better see the time variations of the seismic noise.

In Fig.2 and Fig.3 the time-dependent weekly graphs of H/V and spectra for autumn data from 7.10.2013 to 13.10.2013 are shown. On the x-axis there are frequencies (from 0.05 to 45 Hz) and on y-axis there are (from bottom to top) days of the week from Monday to

Sunday. The zero on y-axis denotes midnight between individual days and colours match amplitude levels according to colour scale.

On the left hand side of *Fig.2* weekly variation of H/V is displayed, on the right hand side there is weekly spectral variation of vertical component shown. In *Fig.3* weekly variations of spectra of horizontal components are displayed. We can notice that increased values of H/V at the lowest and highest frequencies are present during whole week, although slightly daily variability is present at higher frequencies. So it seems that it was not just short time anomaly, but a phenomenon lasting longer. However we do not know exactly by what it was caused.

Further, daily and weekly variability is nicely visible from continuous graphs of H/V and spectrum. At frequencies above 1 Hz, we can clearly observe changes in amplitudes during daily and nightly hours and also differences between working days and weekend, which are correlated with human activities. Mainly the frequencies above 1 Hz are affected as it could be expected due to origin of seismic noise. In *Fig.2* we can notice, that H/V has lower amplitudes at frequencies from 1 Hz to 10 Hz during daily hours while spectra of vertical component (and also of both horizontals, see *Fig.3*) has lower amplitudes during nightly hours. Variation in terms of increased or decreased seismic noise energy from cultural sources is better interpretable from spectrum, since amplitude changes of H/V are dependent on relative changes between spectral components.

Distinct line of increased values is present in H/V and also in spectra at the frequency of 1 Hz and since it is observable only during some days it indicates artificial origin of 1 Hz peak. We can also notice discontinuous sharp line in H/V values, at the frequency of about 6 Hz with counterpart in the spectra, which also indicates artificial origin of the corresponding peak.

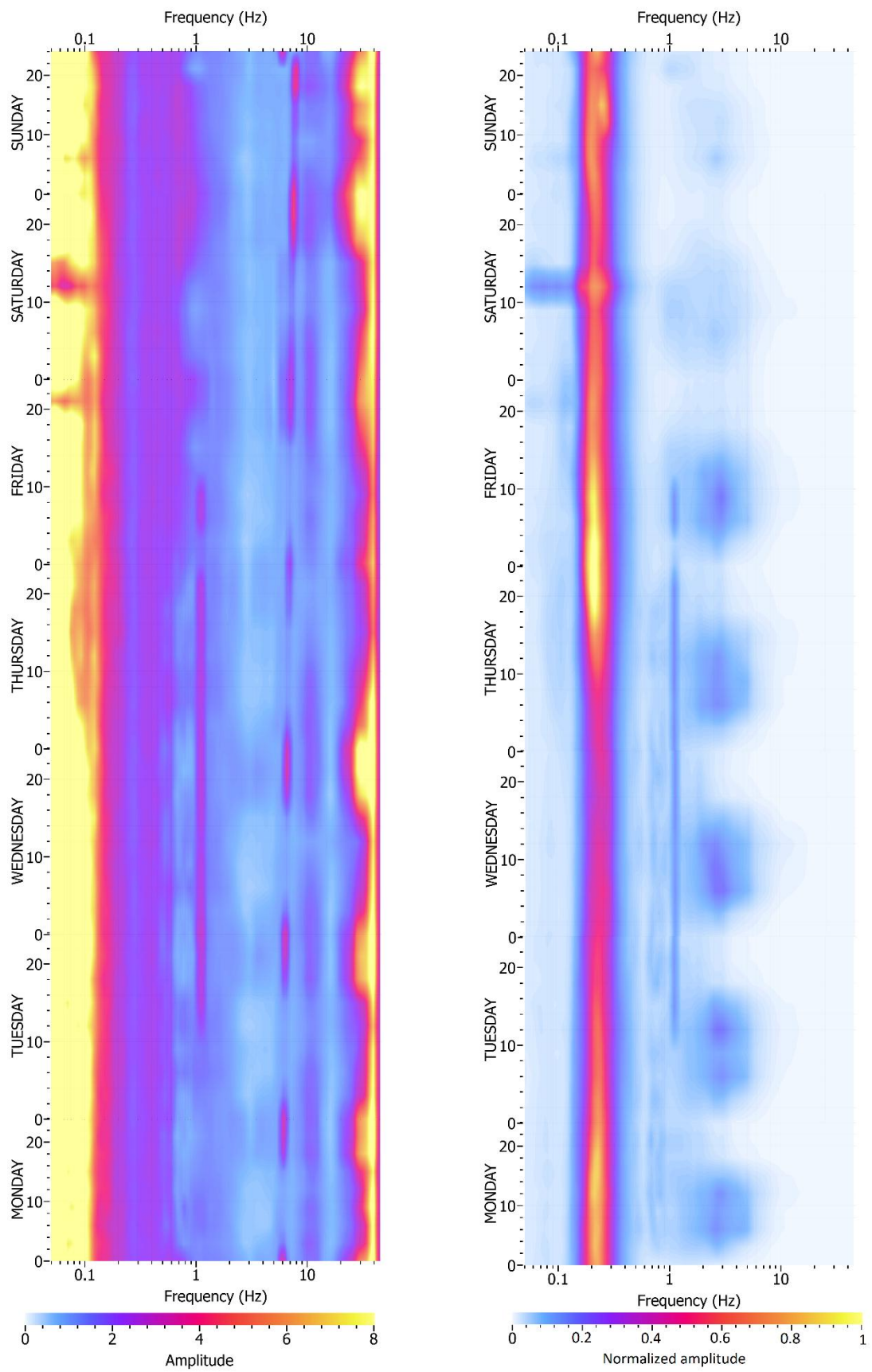


Fig. 2. On the left side is time-dependent graph of H/V ratio and on the right side time-dependent graph of vertical spectral component.

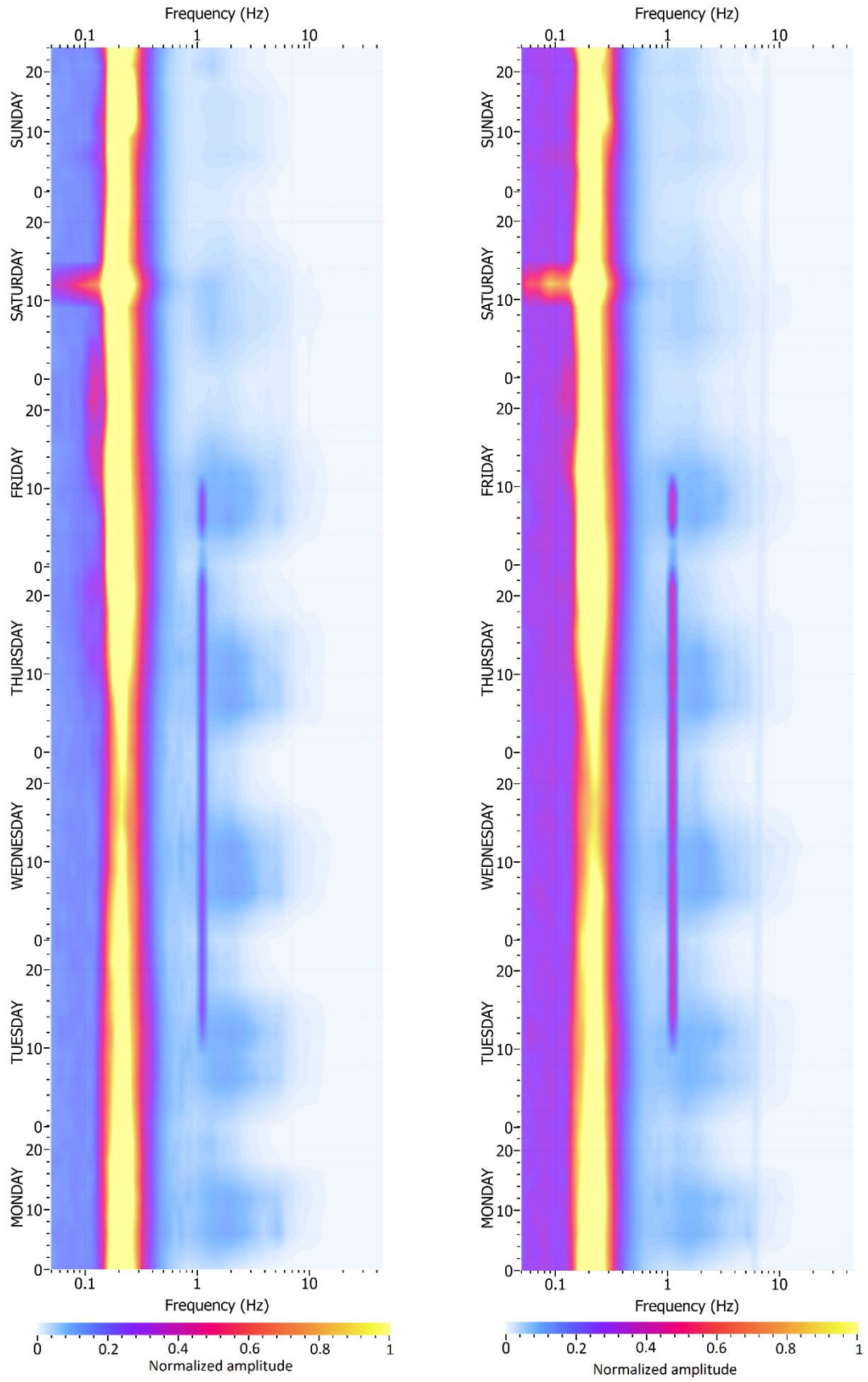


Fig. 3. On the left side is time-dependent graph of spectral N horizontal component and on the right for spectral E horizontal component.

Another observable feature from figures above is the event on Saturday, after 12 o'clock. It responds to the regional earthquake from Greece with the magnitude from surface waves $M_s=6.3$.

Since we did not find out the cause of abnormal character of autumn 2013 H/V results we have performed additional field measurements on the site of seismic station Špačince in autumn 2015. We wanted also to visually check local conditions and surroundings of the station site and to investigate influence of 15 meters deep shaft, where the sensor of permanent station is placed. Our measurement was performed on surface with the sensor of the same type as the one in the shaft. We calculated H/V spectral ratio from data of both sensors, which were recording simultaneously.

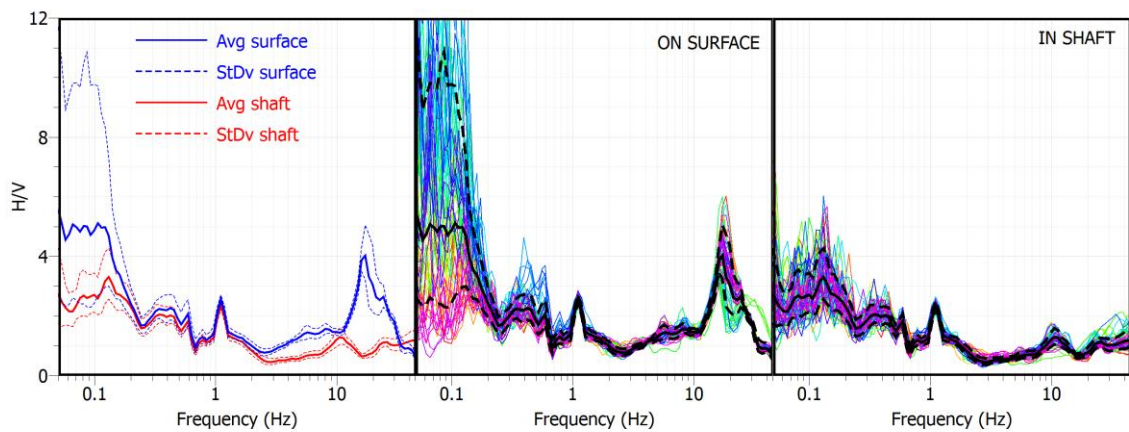


Fig. 4. H/V from seismic stations Špačince. On the most left side there are H/V calculated from measurement on surface (blue) and in shaft (red), solid lines match average values and dashed lines standard deviations. In the middle picture is shown H/V calculated from surface measurement, on the right side is H/V calculated from measurement in 15 meters deep shaft. Colour curves are H/V computed from every 300s time window separately.

Measurement was performed from about 10:00 to 15:00 o'clock, so we had available approximately 5 hours of recorded noise data. H/V curves were computed using software Geopsy. The 300 seconds long time windows were used for calculation. Konno & Ohmachi smoothing with smoothing constant 40 and 5% cosine taper were applied. H/V spectral ratio was calculated for frequencies from 0.05 Hz to 45 Hz.

In Fig. 4. H/V results for autumn 2015 data are displayed. On x-axis of each graph there are frequencies from 0.05 Hz to 45 Hz and on y-axis amplitude of H/V is shown. From this results we can conclude that the main differences between measurement in shaft and on surface are at low frequencies. It can be a consequence of e.g. influence of wind and/or nearby structures. We can also notice differences at frequencies higher than 3 Hz. Results

shows that 15 meters shaft is obviously enough to damp peak which occur at frequency about 17 Hz in case of surface measurement.

Furthermore, abnormal character of H/V occurring in data from autumn 2013 at lowest and highest frequencies is not present in these results. So character of curve calculated from autumn 2013 was probably longer time anomaly, which is not characteristic for autumn season in general. This example illustrate also the fact, that in some cases neither recommended 24 hour measurements for investigation of variability of the results (Hollender et al., 2011) could not be sufficient (in our case an anomaly was present at least during a whole week).

4.1.2 Test of alternative H/V computation

We have created a program code in MATLAB, for computation of H/V according to an alternative formula (7), suggested by Albarello & Lunedei (2013), for more details see Section 3.1. Their study presented just one experimental example, so further analysis is needed. This computational algorithm differs from the commonly used algorithm of H/V calculation, see equation (5), which is implemented also in software Geopsy. We have compared H/V results obtained by using our MATLAB code for alternative way of computation and by using Geopsy implementation.

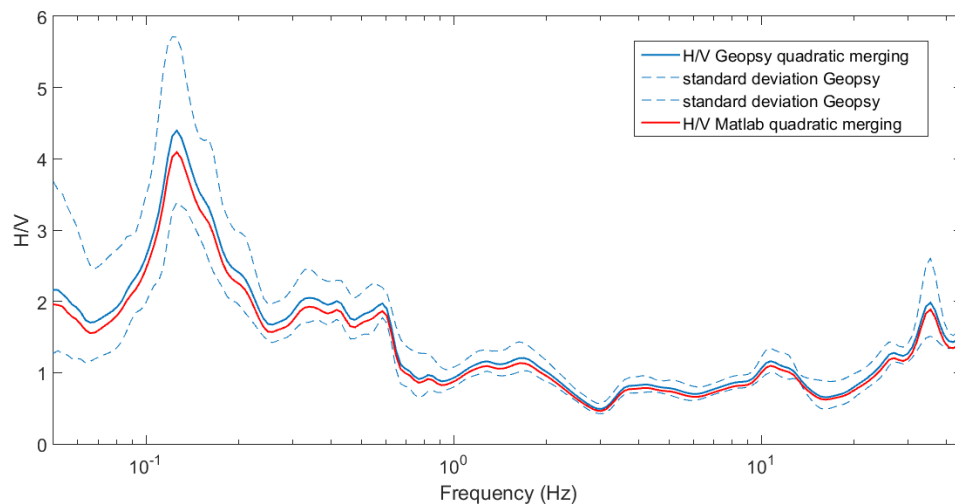


Fig. 5: Comparison of H/V results for seismic station SPAC. Blue solid line denotes average H/V curve computed by Geopsy according to equation (5). Blue dashed lines denote standard deviations of H/V calculated by Geopsy. Red solid line denote H/V curve computed according equation (7).

From the Fig.5 we can see that there is no significant difference between the used algorithms. Differences in amplitude of H/V are within standard deviations and any

significant frequency shift is not observed. In this test we have verified, that using H/V tool of software Geopsy is sufficient for our work and there is no essential need for using algorithm (7) for computation of H/V.

According to *Albarelli & Lunedei (2013)* in the case of computation of H/V according to equation (7), resulting H/V is less biased for all merging procedure (except of case of maximal horizontal values characterized by different convergence behaviour). Therefore we have also verified the influence of different types of averaging procedures for merging horizontal components using algorithm (7). We calculated H/V using 5 different averaging procedures: arithmetic mean, geometric mean, quadratic mean, vector summation and H/V calculated for every horizontal component separately (for formulas see Section 3.1). Results are shown in Fig. 6.

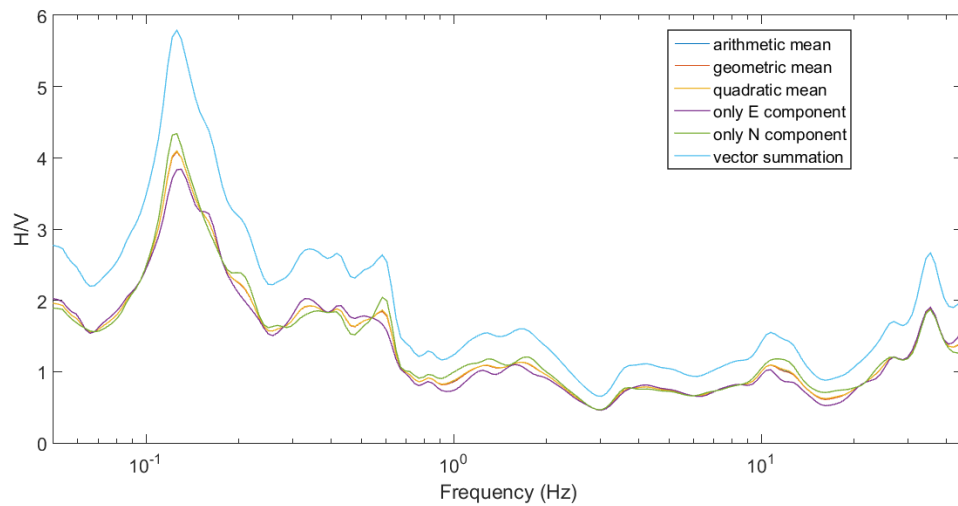


Fig. 6: Comparison of H/V results using different averaging procedure for merging horizontal components. Dark blue curve – arithmetic mean; red curve – geometric mean; orange curve – quadratic mean; violet curve – only E component; green curve – only N component; light blue – vector summation.

In Fig. 6 we can see that H/V curves calculated using arithmetic, geometric and quadratic mean (dark blue, red and orange line) differ within thickness of line. Results for H/V computed separately for N and E horizontal component (green and violet line) differs slightly, what indicates slight lateral heterogeneities. The H/V curve for which the horizontal components have been merged using vector summation has higher amplitude, however frequencies of the peaks stay unaltered. Higher amplitudes are expected due to different normalization.

4.2 Analysis of H/V spectral ratios computed from data of permanent seismic stations

In this section we will summarize main results from analysis of H/V spectral ratio computed for these 14 permanent seismic stations (see *Fig. 42*) in source zone Malé Karpaty: Banka, Buková, Dobrá Voda, Hradište, Jaslovské Bohunice, Jalšové, Katarínka, Lakšárska N. Ves, Lančár, Modrá, Plavecké Podhradie, Podolie, Pustá Ves, Smolenice. Results for seismic station Špačince are already in more details discussed in section 4.1.1 and in our bachelor thesis. Information about seismic stations are marked in *Table 2*.

For every seismic stations H/V spectral ratios from daily hours, from 09:00 to 13:00 and from nightly hours 00:00 to 04:00 have been computed. Based on parametric tests provided in our bachelor thesis and recommendations of SESAME, parameters of computation have been selected. Four hours long data were divided into 300 s long time windows. For computation was used Konno & Ohmachi smoothing with smoothing constant 40 and 5% cosine taper. H/V curves were computed for frequencies 0.05 Hz to 45 Hz with sampling 100. If it was needed for analysis of results, parameters was changed and character of the reprocessed H/V curve was investigated.

For computation H/V, tool in software Geopsy was used and for interpretation of peaks several other tools of Geopsy software were used: computation of spectrum, time-frequency analysis, damping, rotate spectrum and rotate H/V (www.geopsy.org). Using of these tools helps with interpretation of results and one can obtain indications of artificial origin of peak.

<i>Station</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Sensor type</i>	<i>Depth</i>	<i>Operator</i>
Banka (BANK)	48° 33' 51.5"	17° 51' 29.2"	Lennartz 1 s	0 m	*
Buková (BUKO)	48° 32' 35.0"	17° 24' 34.7140''	Guralp 10 s	0 m	Progseis
Dobrá Voda (DVOD)	48°36'24.2047"	17°32'04.1312''	Guralp 10 s	4 m	Progseis
Hradište (HRAD)	48°37'25.7263"	17°29'40.3122''	Guralp 10 s	0 m	Progseis
Jaslovské Bohunice (JABO)	48°29.922'	17°41.877'	Guralp 1 s	8 m	Progseis

Jalšové (JALS)	48° 30' 45.0"	17° 49' 56.6"	Guralp 10 s	0 m	*
Katarínka (KATA)	48°32.96136'	17°33.12233'	Guralp 10 s	6 m	Progseis
Lakšárka N. Ves (LAKS)	48°34.3498'	17°12.8747'	SM-3	6 m	Progseis
Lančár (LANC)	48°35' 52.8287"	17°38' 56.9822''	Guralp 10 s	0 m	Progseis
Modra (MODS)	48° 22' 25.0"	17° 16' 38.6"	STS-2N	0 m	ESI SAS
Plavecké Podhradie (PLAV)	48°29.0747'	17°15.6639'	Guralp 10 s	0 m	Progseis
Podolie (PODO)	48° 40' 58.1"	17° 42' 47.5"	Guralp 10 s	0 m	*
Pustá Ves (PVES)	48°37'58.8750"	17°38' 15.2262''	Guralp 10 s	7 m	Progseis
Smolenice(SMOL)	48° 30' 48.80"	17° 25' 58.34''	Guralp 1 s	0 m	Progseis
Špačince (SPAC)	48°26' 03.7218"	17°37' 16.8743''	Guralp 10 s	15 m	Progseis

Table 2: Information about seismic station: Name of stations, latitude, longitude, type of sensor, placement of sensor in depth, operator of seismic station. ESI SAS marks Earth Science Institute of Slovak Academy of Science in Bratislava and symbol * marks cooperation of three institutions: Earth Science Institute of Slovak Academy of Science in Bratislava, The Institute of Rock Structure and Mechanics of the Czech Academy of Sciences and company Progseis.

As follows H/V results with spectrum, for every seismic station, are presented. Amplitudes of each spectral component, for one seismic station, are scaled on the same value and normalized at value one according to the component with highest amplitude value.

4.2.1 Banka

In Fig. 8 there are spectra of each component of seismic noise recordings from station BANK displayed. H/V results for station BANK are shown in Fig. 9. In both figures, curves from nightly and also daily hours are displayed.

Seismic noise data from daily hours in the time domain contain many transients. It was not possible to remove all transient time windows, since transients were present in every time window. From nightly hours we have seismic noise with better quality, without many transients. This can be seen also in frequency domain, frequency content from day and night differs mostly in microtremor range, which is affected by human activities. For that reason we consider H/V computed from nightly hours to be more reliable for interpretation.

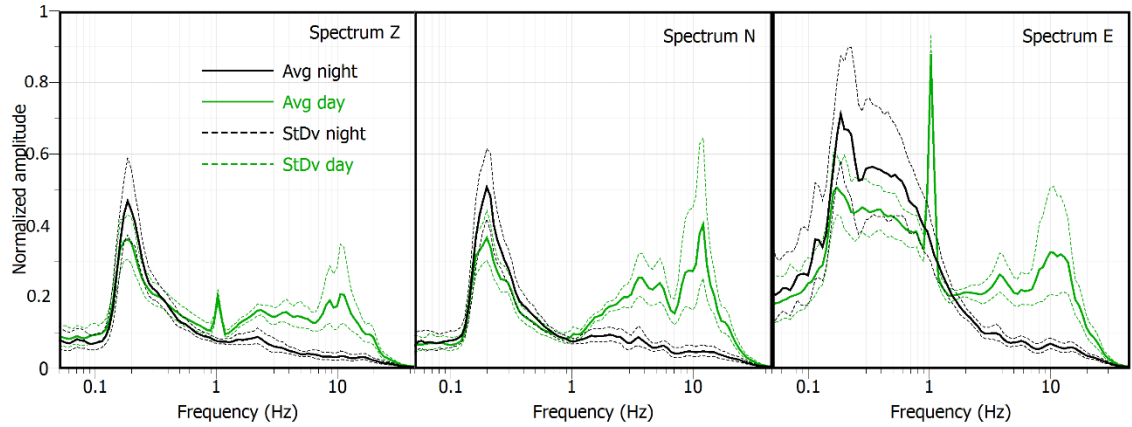


Fig. 7: Normalized spectrum of seismic noise for Banka seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

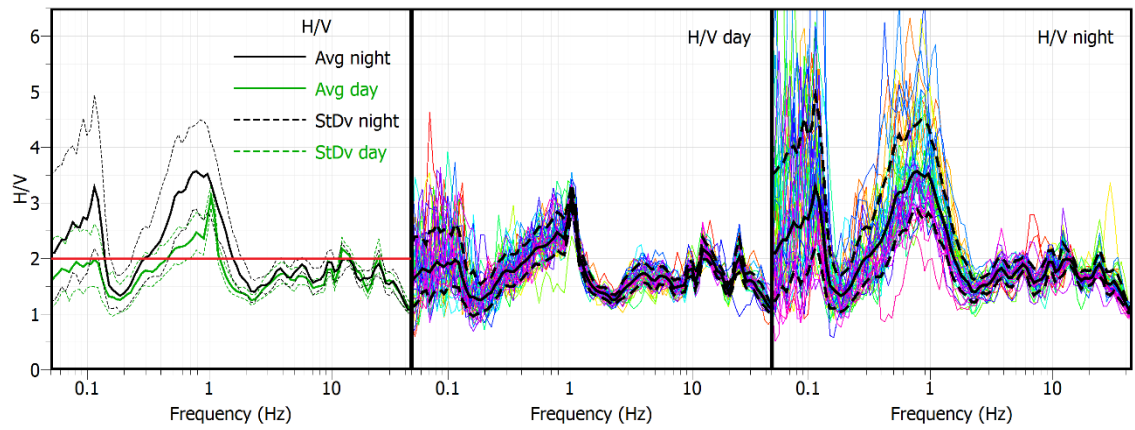


Fig. 8: H/V results for Banka. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

Spectra from east-west and from north-south have clearly different character, what can indicate the effect of 2D, respectively 3D local geological structure at the site. This leads also to different H/V ratios when computed by using each horizontal component separately.

According to SESAME criteria of reliability of H/V results (see also 3.4.1) only the peaks with amplitude exceeding value 2 should be considered.

Peak around 0.12 Hz, although does not exceed value 2 during day looks to be caused by natural sources and it is considered in further analysis. Broad multiple peak from approximately 0.53 Hz to 1 Hz looks reliable, except for sharp peak at 1 Hz (from daily H/V). Spectrum of Z and E component from daily hours and also time-frequency analysis (see Fig.

10) clearly indicate its artificial origin. On the TFA from 10:25 to 10:50 hour a narrow spectral line at the 1 Hz is visible together with band of transients at the higher frequencies. Therefor we exclude 1 Hz peak from out further analysis. Peaks of H/V curve at higher frequencies have amplitudes slightly higher than 2 during a day only, when the transients often occur at these frequencies. Therefore, we do not consider these peaks in the further analysis.

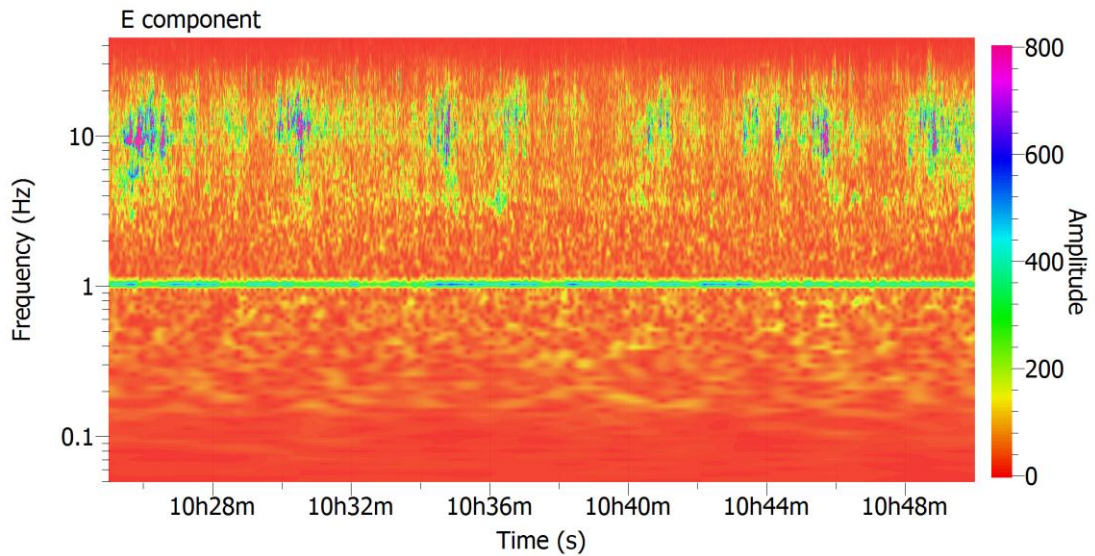


Fig. 9. Time frequency analysis computed from 25 minutes long period of daily seismic noise for E component.

4.2.2 Buková

Fourier spectra from seismic noise recorded in BUKO seismic station are displayed in *Fig. 10*. H/V for this station are shown in *Fig. 11*.

Recording of seismic noise from BUKO station in time domain does not exhibit transient signals. Criteria of significance are satisfied only by peak at frequency about 0.1 Hz. Another peak which reaches value 2 only during night is at frequency about 0.88 Hz, this peak has probably natural origin. Multiple peak at about 8-10 Hz, which slightly reaches value 2 is probably industrial, since at this frequency band many transients are present during both, day and night on TFA (*Fig. 12*), therefore we do not consider this peak to be reliable. TFA (see *Fig. 12*) indicates also artificial origin of trough at 5.5 Hz.

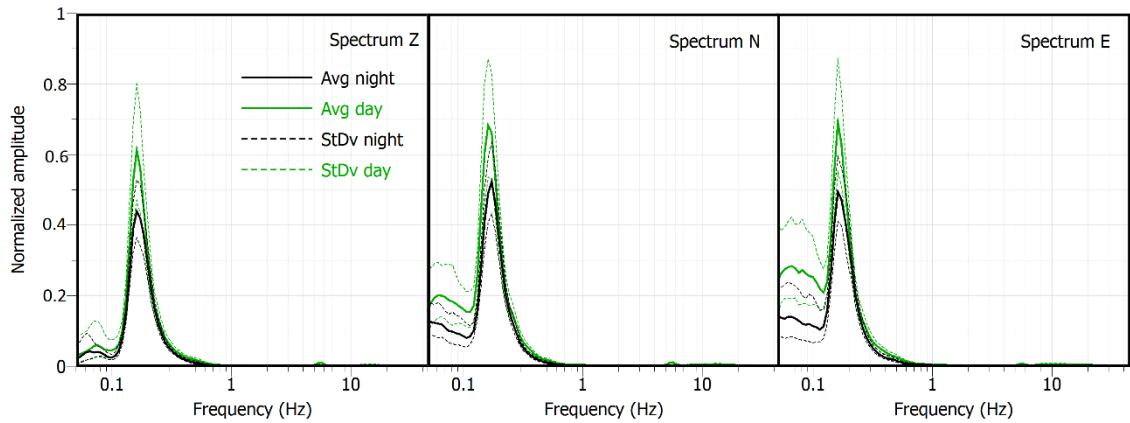


Fig. 10: Normalized spectrum of seismic noise for Buková seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

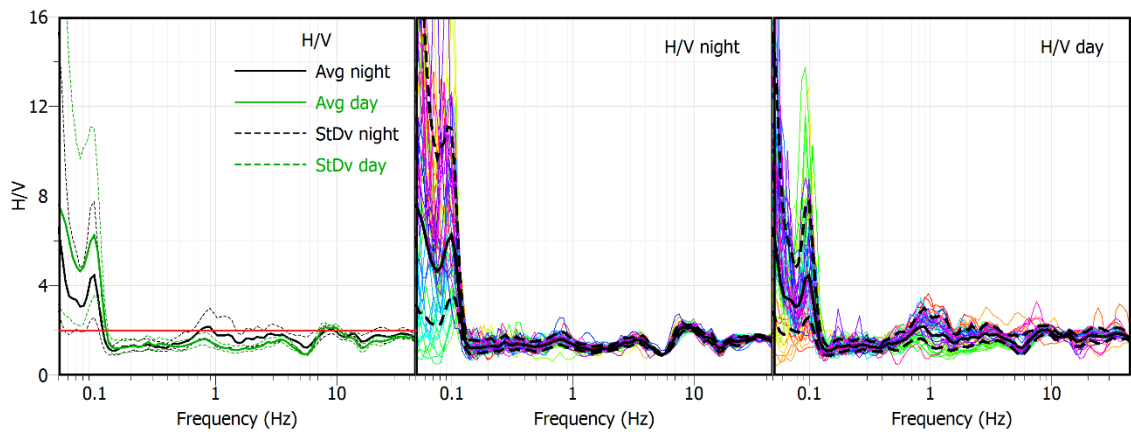


Fig. 11: H/V results for Buková. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

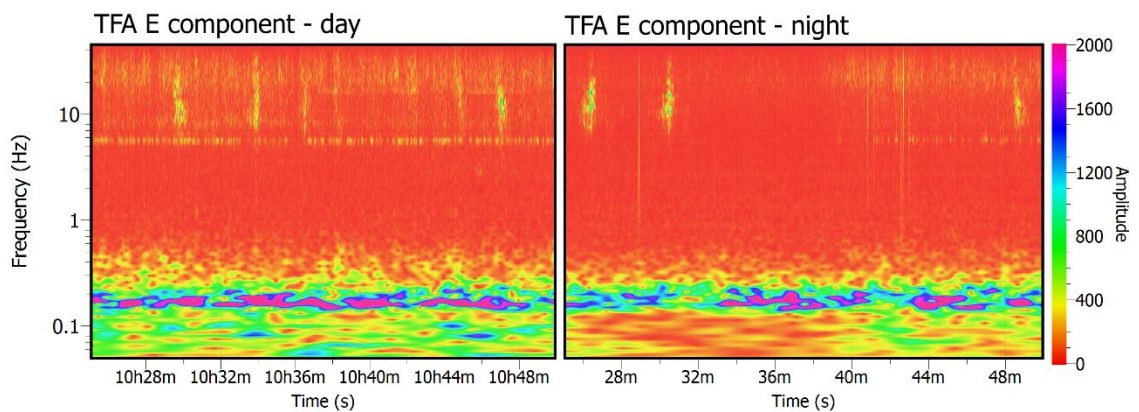


Fig. 12: Example of TFA result from E component for 25 minutes long recording from day on left and night on right side.

4.2.3 Dobrá Voda

In Fig. 13 are displayed spectra for each spatial component of seismic noise and in Fig. 14 are shown H/V results.

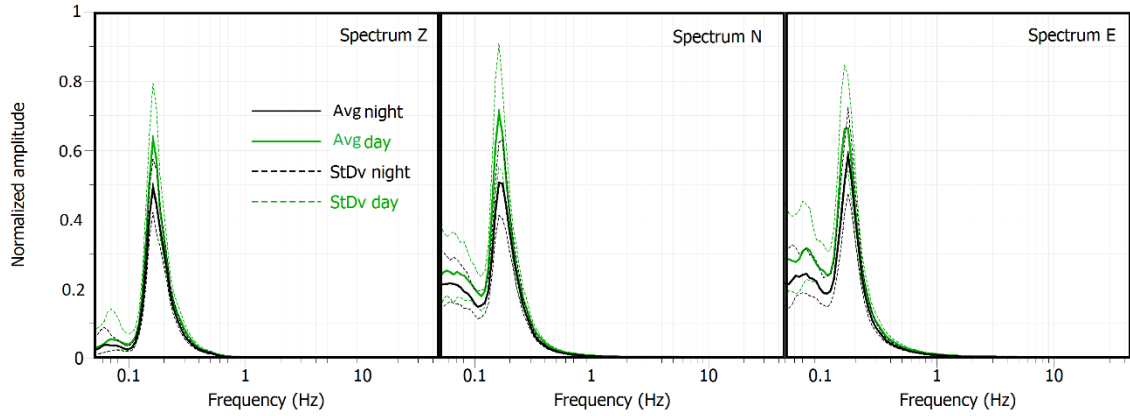


Fig. 13: Normalized spectrum of seismic noise for Dobrá Voda seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

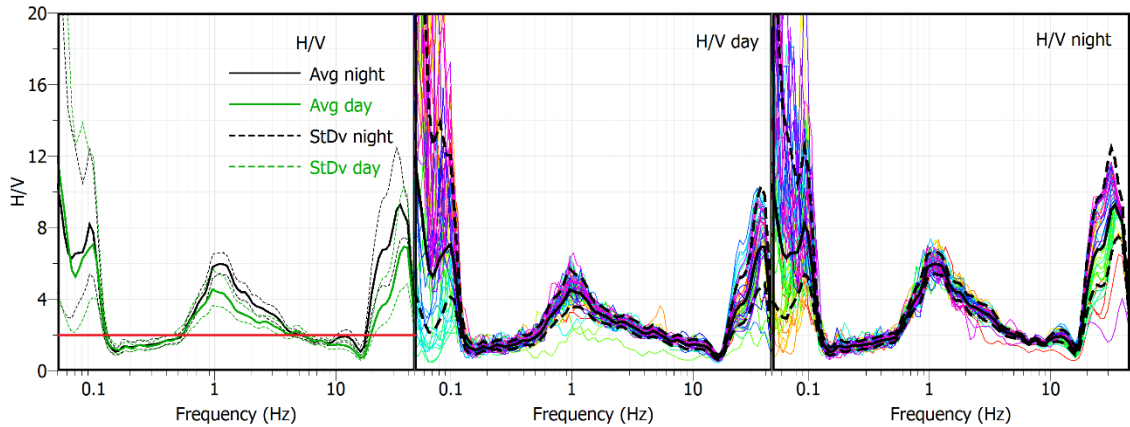


Fig. 14: H/V results for Dobrá Voda. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

In the time domain, the seismic noise recordings from DVOD seems to be reliable, same can be seen from spectra in frequency domain for both periods, daily and nightly. Just a few transients were present and they are visible on H/V curves like the outlying curves. We have recalculated H/V also with rejection of corresponding time windows and found out that they do not have in this case significant impact on the resulting H/V.

In this case H/V exhibits three peaks, which satisfy SESAME criteria and there are no indications of their artificial origin. The first peak slightly varies during night and day about

frequency 0.1 Hz. The second wide peak H/V exhibits at about 1 Hz, his amplitude is higher during night. The third is high frequency peak at about 37 Hz. We do not exclude any of these peaks from further analysis.

4.2.4 Hradište

In Fig. 15 are pictured spectra for each spatial component for seismic station Hradište and in Fig. 16 are shown results of H/V spectral ratio.

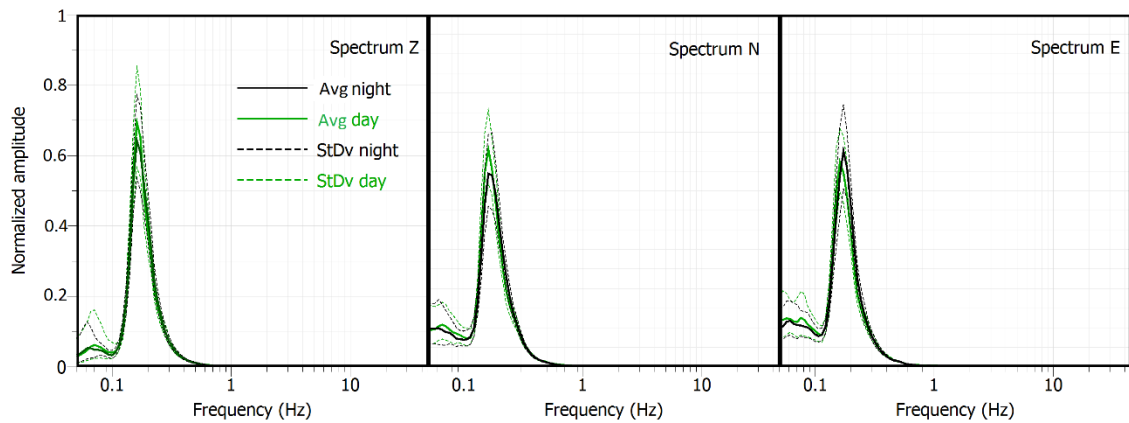


Fig. 15: Normalized spectrum of seismic noise for Hradište seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

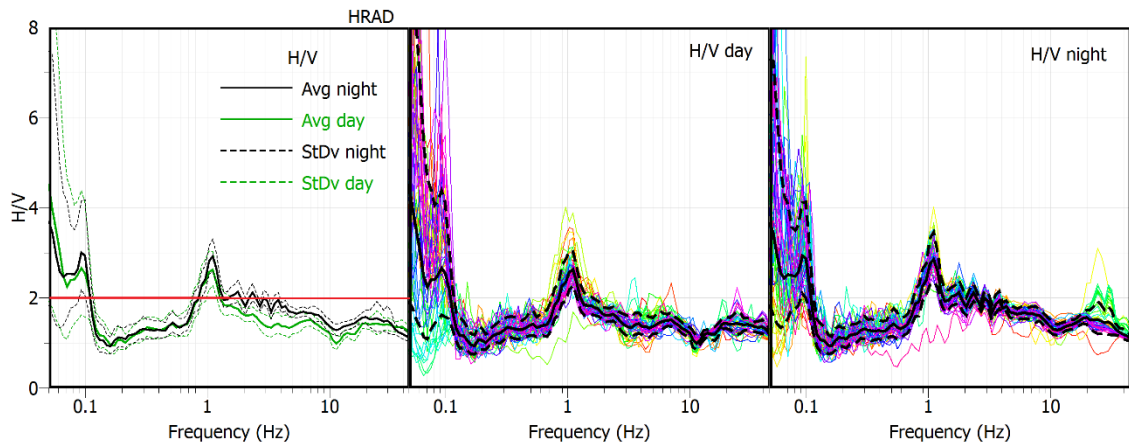


Fig. 16: H/V results for Hradište. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

Low frequency microseismic peak at around 0.09 Hz and peak around 1 Hz probably do not have artificial origin, so we consider them in further analysis. Differences between H/V curves which are calculated from daily and nightly hours can be seen at higher frequencies

above 1 Hz. There are four smaller higher frequency peaks are only on nightly H/V curve, this time variability indicates their artificial origin, and it was confirmed also by TFA.

4.2.5 Jaslovské Bohunice

In Fig. 17 and Fig. 18 are shown results of the spectrum and the H/V for station Jaslovské Bohunice. Since the station is in close proximity of the nuclear power plant there is present many of the anthropogenic sources which have significant impact on seismic noise recordings. It can be seen also on spectrum of each space components, which have sharp peaks in microtremor's frequency range, so above 1 Hz. Therefore, we consider for reliable only peaks under frequency approximately 1 Hz.

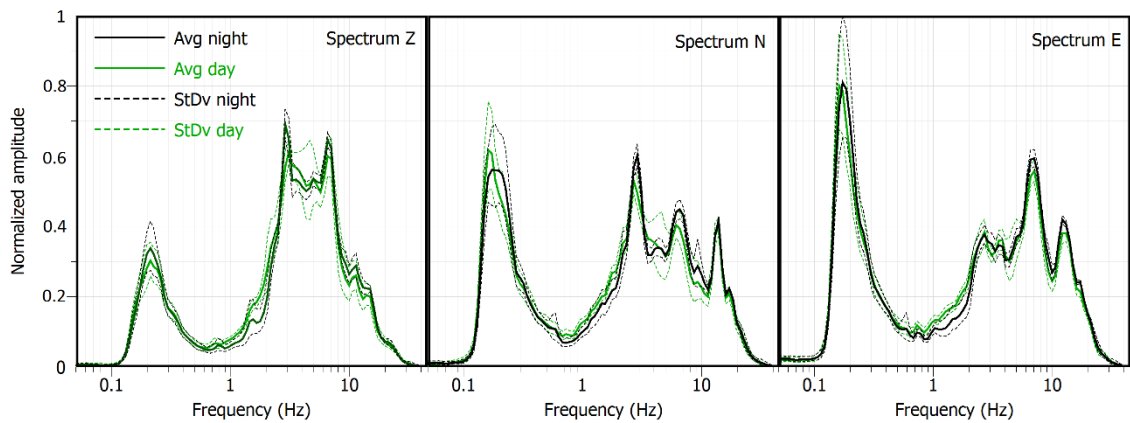


Fig. 17: Normalized spectrum of seismic noise for Jaslovské Bohunice seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

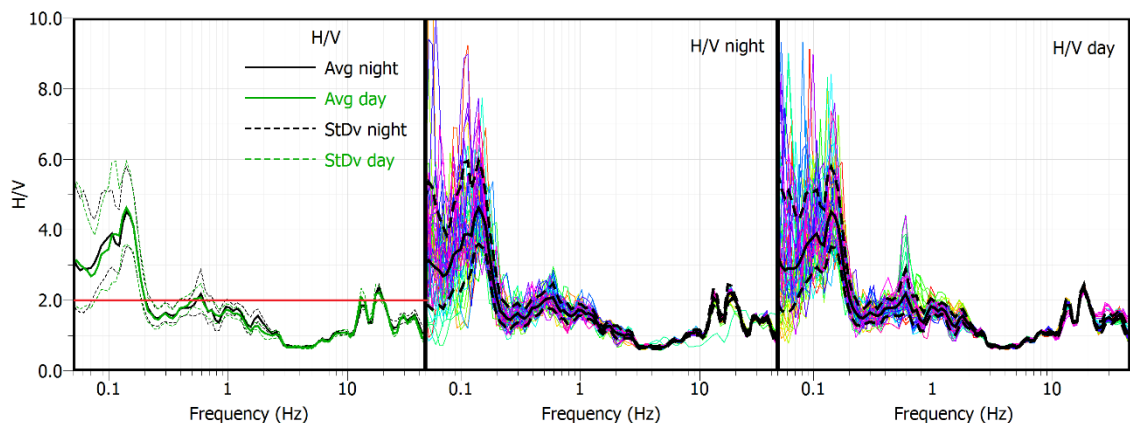


Fig. 18: H/V results for Jaslovské Bohunice On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

Amplitude value 2 is exceeded by a multiple peak in a frequency range from 0.11 Hz to 0.14 Hz. The peak at 0.58 Hz slightly reaches amplitude value 2, artificial origin was not found. Higher frequencies peaks have artificial origin, what is possible to see on spectrum and also on TFA.

4.2.6 Jalšové

Results of spectra and H/V for station JALS are pictured in *Fig. 19* and *Fig. 20*.

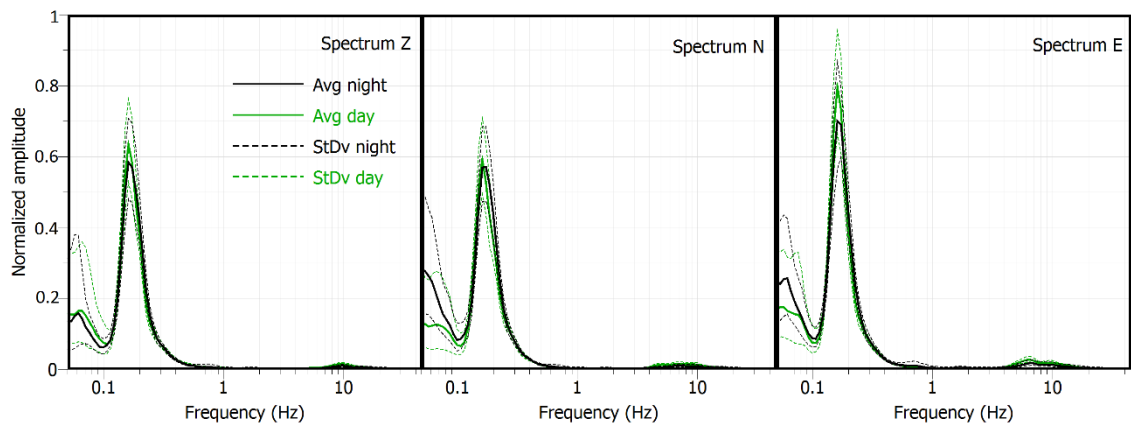


Fig. 19: Normalized spectrum of seismic noise for Jalšové seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

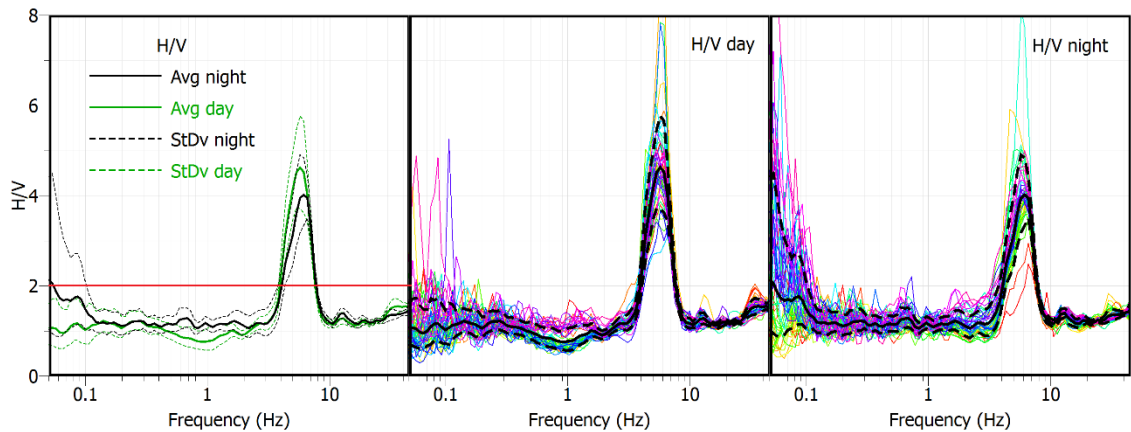


Fig. 20: H/V results for Jalšové. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

H/V curve exhibit just one significant peak, at frequency about 5.9 Hz. We have tried to identify origin of the peak using TFA, damping technique, H/V rotate and neither of this methods indicate artificial origin. However we have been cautious about interpretation of this peak, since in close proximity of sensor is pump. Another day was chosen for

computation of H/V in order to check if peak is still present. Results are shown in *Fig. 21*. But test confirmed the presence of peak, which seems to be solid and time independent. And moreover we reprocessed H/V with different value of smoothing parameter (see *Fig. 22*), shape and amplitude stay the same, what indicates natural origin of the peak. Therefore we did not find out artificial origin of the peak and we will consider this peak in further analysis.

The sharp increase at the lowest frequencies of red H/V curve (see *Fig. 21*) is probably caused by wind.

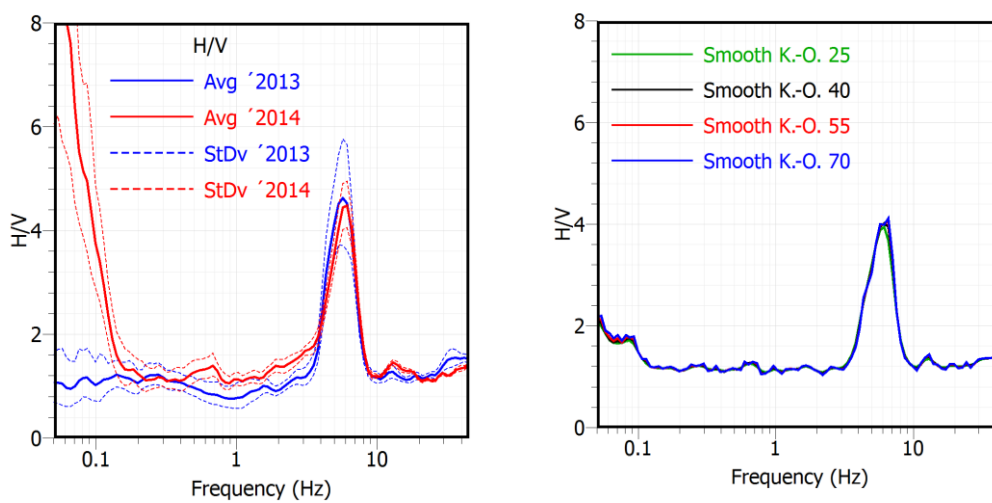


Fig. 21 & Fig. 22: Picture on the left side: Comparison of H/V curves from 31.1.2013 (blue lines) and 31.1.2014 (red lines). Solid lines are average curves and dashed lines are standard deviations. Picture on the right side: Comparison of H/V reprocessing with different Konno & Ohmachi smoothing parameters.

4.2.7 Katarínka

Spectra calculated from seismic noise recorded on seismic station KATA are displayed in *Fig. 23* and H/V results are in *Fig. 24*.

Character of H/V curves from night and day differs markedly about frequency 1 Hz. Nightly H/V curve has peak, while daily H/V curve exhibits trough. Spectra from night and day do not provide indications of artificial origin. However on vertical component of TFA is clearly visible sharp monochromatic peak at frequency 1 Hz, while on horizontal it is not so significant. Example of TFA results is shown in *Fig. 25*. We exclude sharp peaks at approximately 0.9 Hz and 1.4 Hz from further analysis since they have artificial origin and

consider only wide peak centred about frequency 1 Hz, which is present on nightly H/V curve. We consider also low frequency peak at about 0.1 Hz for next analysis.

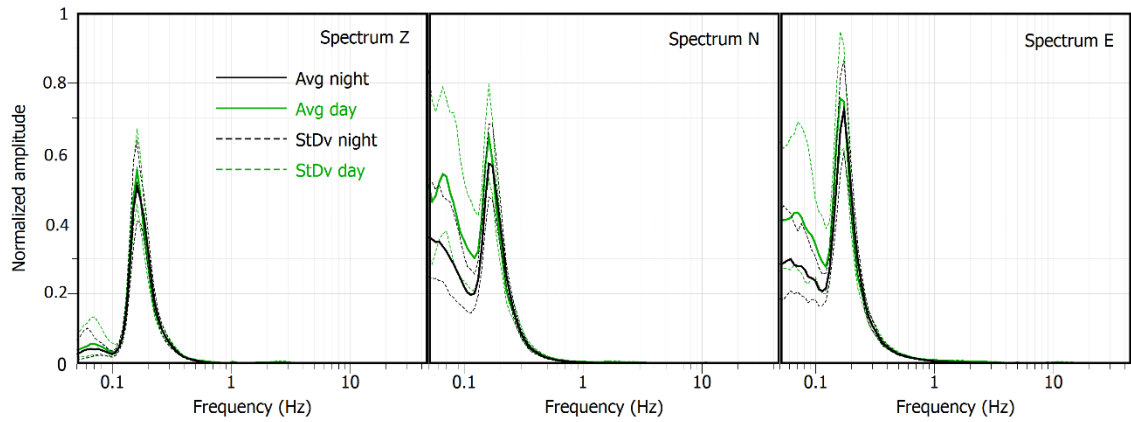


Fig. 23: Normalized spectrum of seismic noise for Katarínka seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

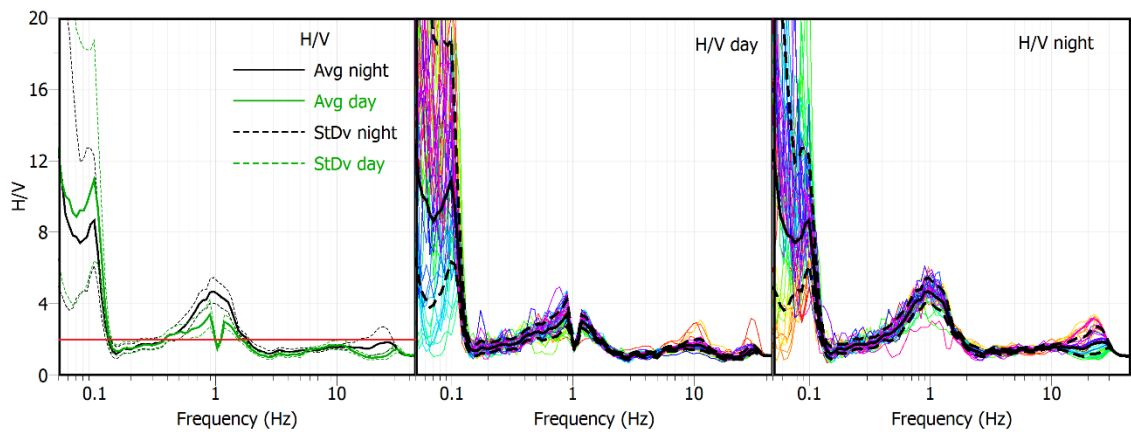


Fig. 24: H/V results for Katarínka. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

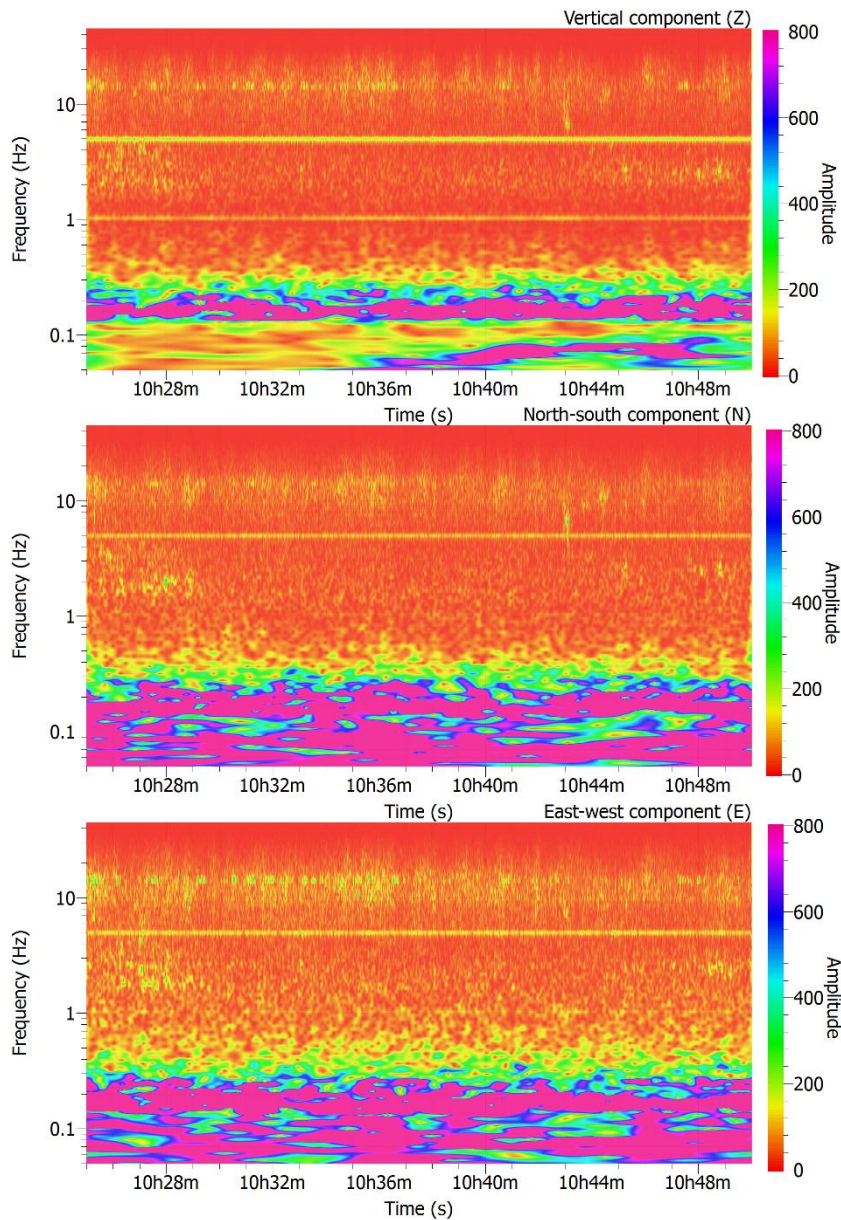


Fig. 25: TFA computed for 25 minutes long period, from 10:25 to 10:50 for each spatial component, vertical (Z) and two horizontal – north-south (N) and east-west (E).

4.2.8 Lakšárska Nová Ves

The seismic noise recordings from this station contains many transients, mainly during the daily hours. The calculations were realized with and also without rejection of time windows. Selection of windows, in this case, does not significantly affects results.

Spectra from day and night, which are shown in Fig. 26, do not exhibit considerable differences. Interesting is the amplitude difference between north-south (N) and east-west (E) spatial component in frequency domain and also in time domain. This can indicate directional dependence of seismic noise on site. Therefore we have checked also

directional dependence of H/V using tool H/V rotate of software Geopsy and also by computing separately H/V for N and E horizontal components.

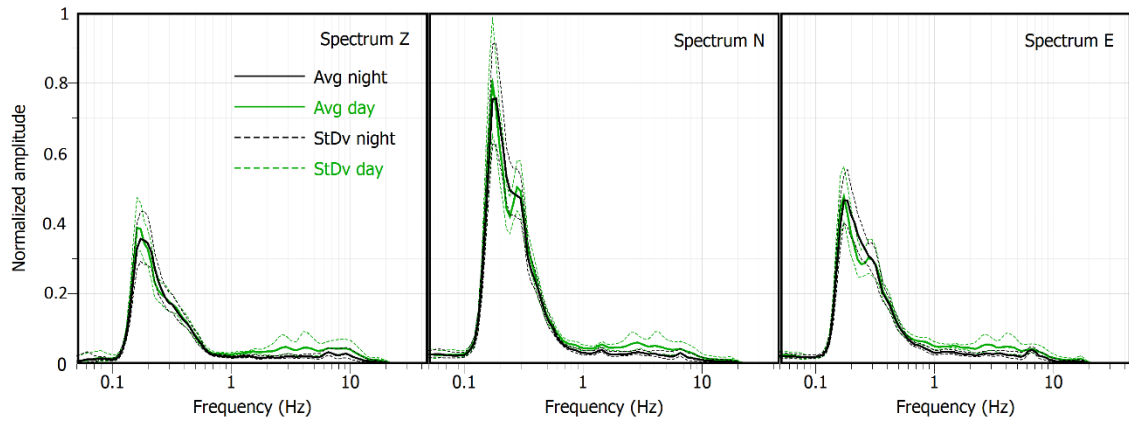


Fig. 26: Normalized spectrum of seismic noise for Lakšárka Nová Ves seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

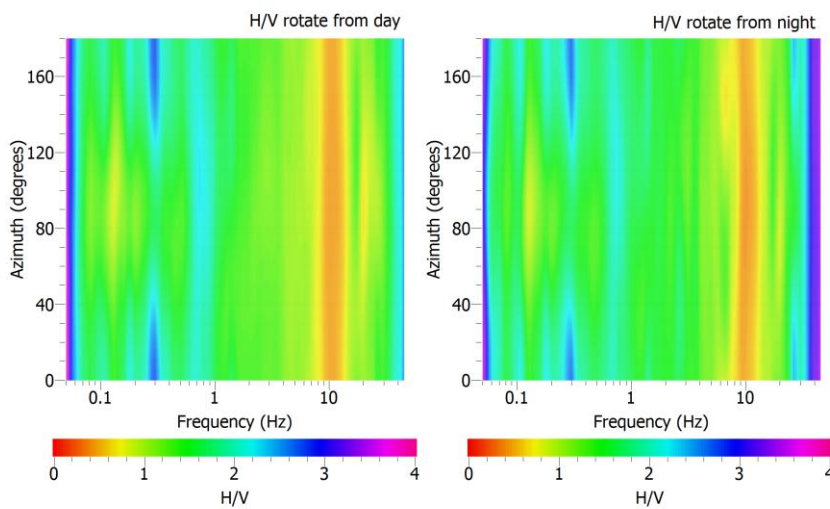


Fig. 27: H/V rotate calculated from 0° to 180° every 10°, the 180°-360° being symmetry of the 0°-180°. On the left side is H/V rotate computed from daily hours and on the right side is H/V rotate computed from nightly hours. The 0° direction indicates the North direction and the 90° direction indicates the East direction.

H/V rotate (see Fig. 27) indicates polarization of H/V in microseismic frequency range mainly in east-west direction. Although trough at about 10 Hz has no preferably direction, TFA indicates his artificial origin, since sharp peak is present on Z spatial component.

H/V curves (Fig. 28) do not have any clear peak, it is difficult case for interpretation. Value two is exceeded just slightly by two peaks. They are not very good defined but we will consider them in further analysis. We consider also the peak at about 0.1 Hz, since this peak with slightly frequency variability, is present for the every station of source zone Malé Karpaty (nonetheless his amplitude does not exceed value 2).

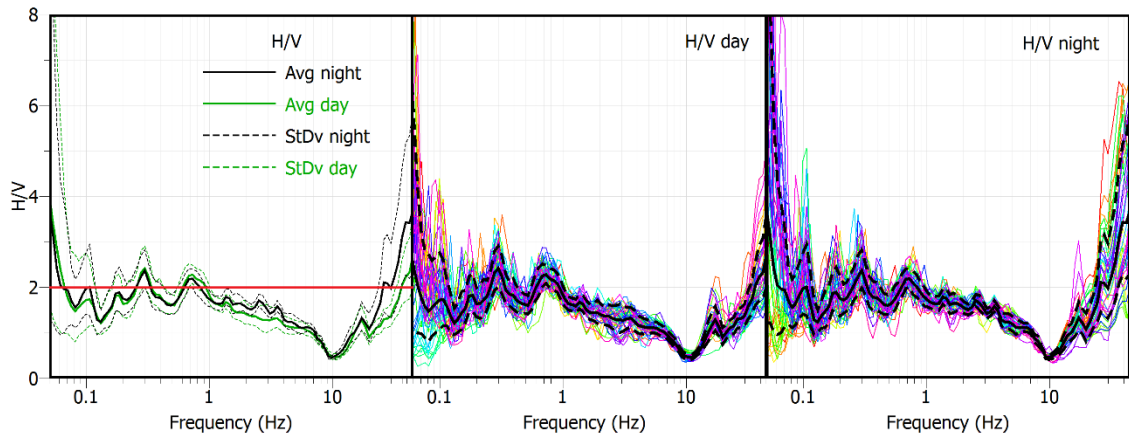


Fig. 28: H/V results for Lakšárska Nová Ves. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

4.2.9 Lančár

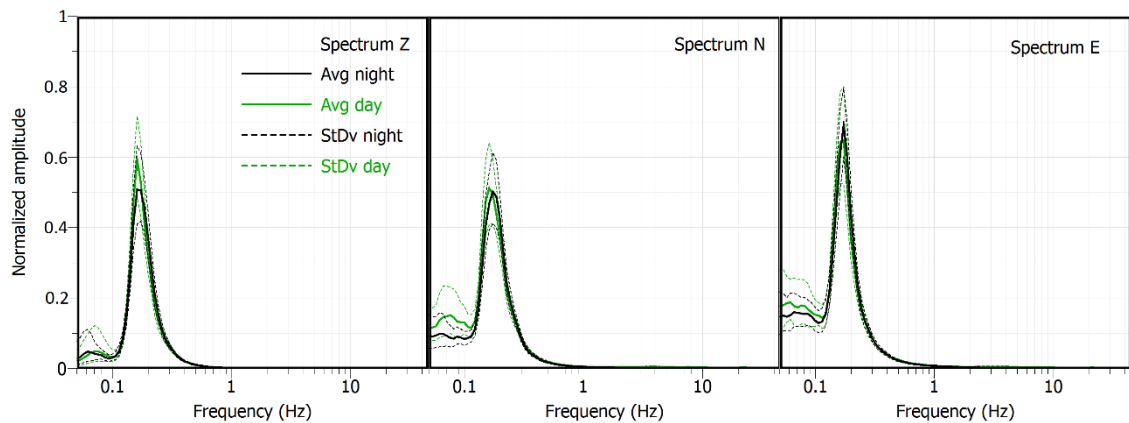


Fig. 29: Normalized spectrum of seismic noise for Lančár seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

In this section are presented results from seismic station LANC. In Fig. 29 are shown spectra and in Fig. 30 are pictured H/V results.

Data in time and frequency domain does not exhibit obvious anomalies. The frequencies of the peaks on the H/V curves are stable during a day and a night, however the H/V from the night has bigger standard deviations. Outlying H/V curves belong to the same part of seismic noise recordings and after removing of corresponding time windows character of H/V curve from night was better defined.

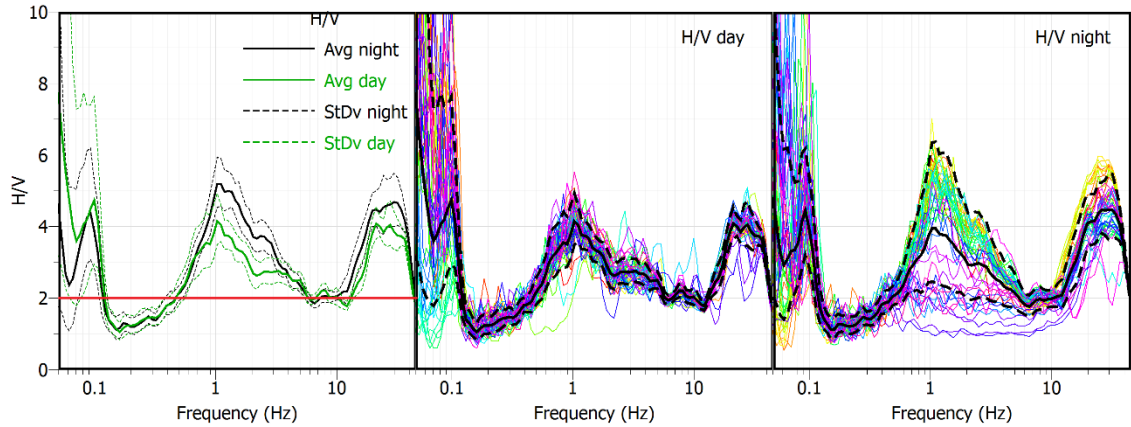


Fig. 30: H/V results for Lančár. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

H/V spectral ratio exhibits three significant peaks. The first at about 0.09-0.1 Hz, the second is wide peak at about 1 Hz and the third is multiple wide peak at about 20-30 Hz. For neither of them have not been detected artificial origin.

4.2.10 Modra

In Fig. 31 and Fig. 32 are shown spectra and H/V results. The seismic noise recordings in time and frequency domain does not exhibit obvious anomalies. The H/V and the spectra have well defined average values with just small standard deviations.

H/V spectral ratio does not exhibit any significant peaks, it is expected since seismic station is placed on rocky subsoil. We consider only peak at about 0.1 Hz, since it is present for every location of our zone of interest.

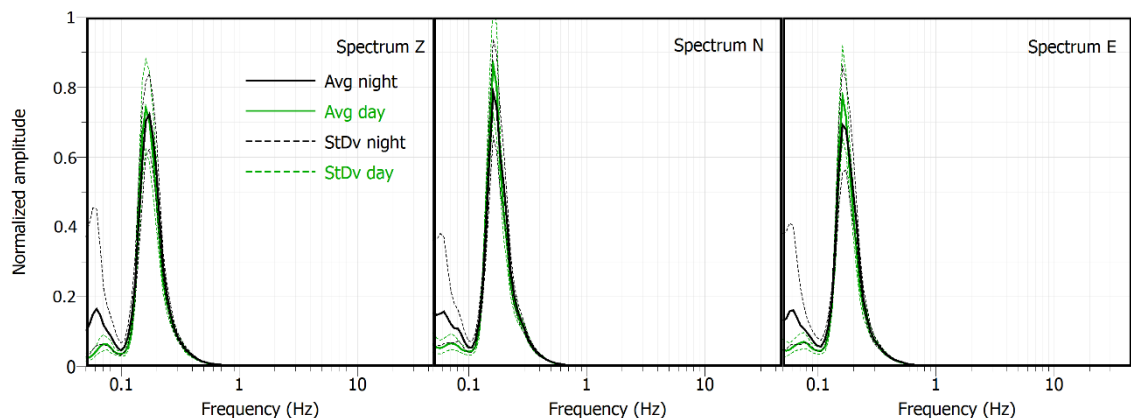


Fig. 31. Normalized spectrum of seismic noise for Modra seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

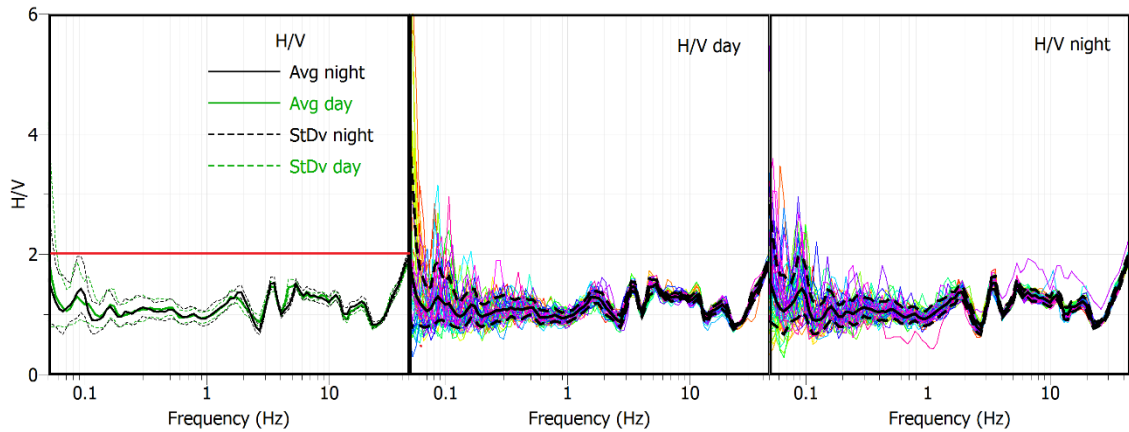


Fig. 32. H/V results for Modra. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

4.2.11 Plavecké Podhradie

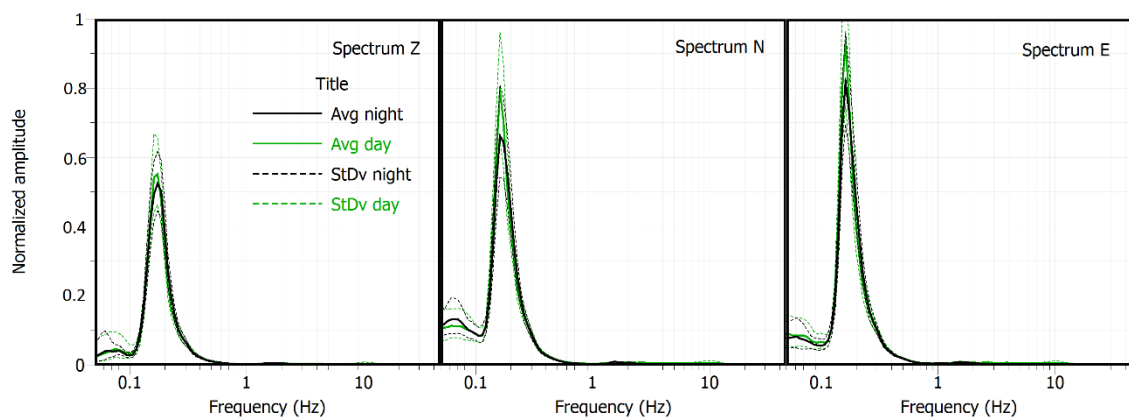


Fig. 33: Normalized spectrum of seismic noise for Plavecké Podhradie seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

In picture Fig.33 are displayed spectra and in Fig.34 are shown H/V curves. Both are consistent in shape during nightly and daily hours. Outlying H/V curves which are visible in Fig.34 correspond to transients and H/V was calculated also without corresponding time windows. Due to sufficient number of time windows it does not affect resulting character of H/V curve.

The most significant peak of resulting H/V is at about 0.1 Hz. Other two peaks exceeds amplitude value 2 but they are not very well defined. The first is about 1 Hz and the second is at approximately 5 Hz. The third peak is at 2.7 Hz and exceeds value 2 only on H/V calculated from daily hours. The TFA from night exhibits in the frequency band from roughly 2.3 to 3.3 Hz strip of increased values.

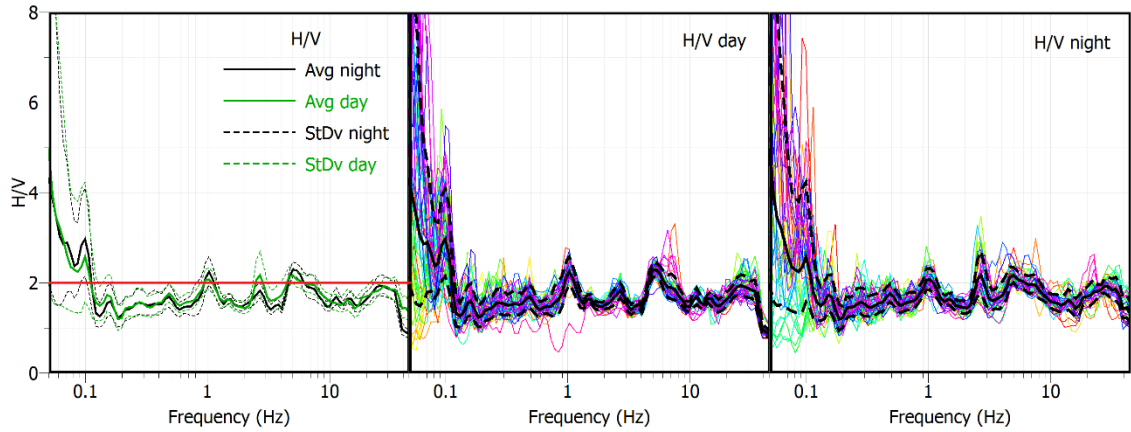


Fig. 34: H/V results for Plavecké Podhradie. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

4.2.12 Podolie

The spectra (see Fig. 35) have no significant daily variability. We can notice from Fig. 35 asymptotical increasing values for the lowest frequencies on horizontal components. It can be possibly caused by bad weather conditions.

Significant peaks are: peak at 0.1 Hz and wide very expressive peak centred about 1 Hz. On slope of nightly 1 Hz peak are added like others not well defined peaks. Another peak at 3 Hz, is present only on daily H/V and has probably anthropogenic origin so it is not considered in further analysis.

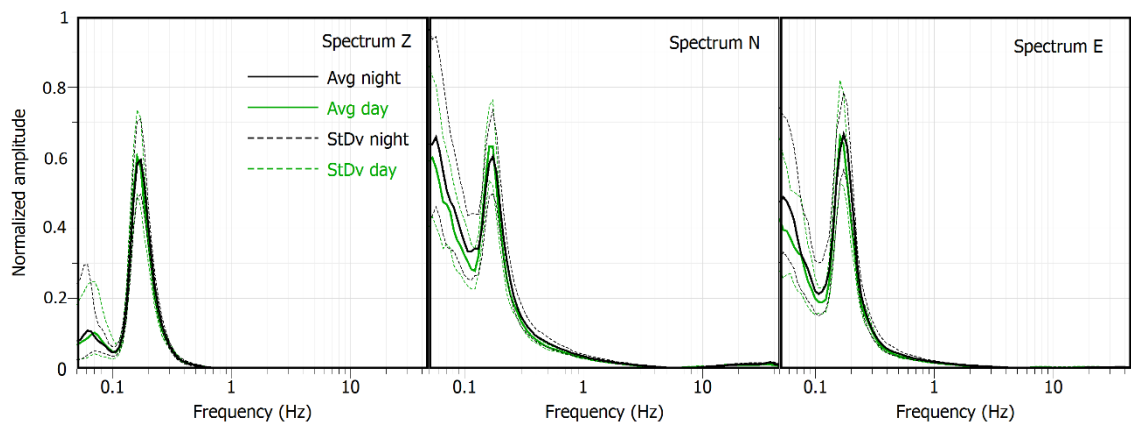


Fig. 35: Normalized spectrum of seismic noise for Podolie seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

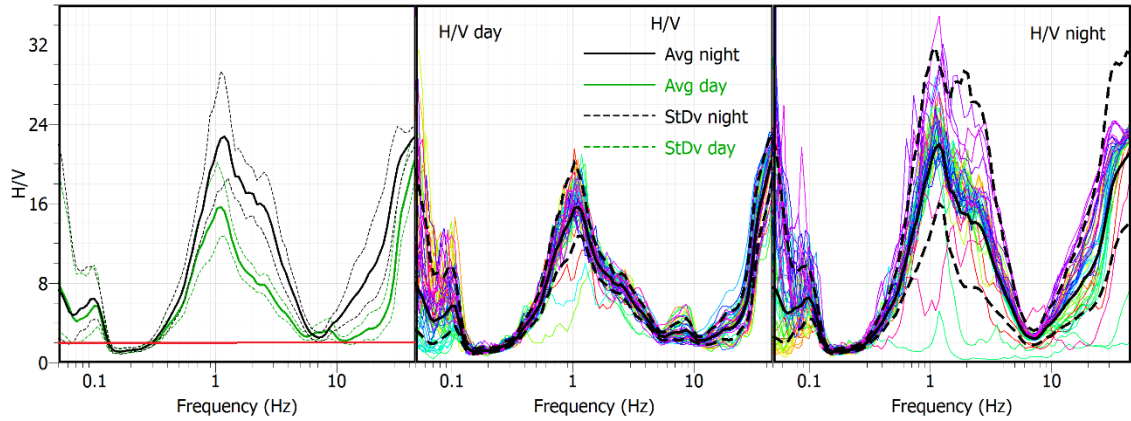


Fig. 36: H/V results for Podolie. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

On TFA, of station PODO, is not visible any anomaly at low frequencies, only several high frequency transients are present at about 20 – 40 Hz. Outlying colour H/V curves on H/V night (Fig. 36) are caused by transients, in case of their removing, H/V has become more solid, but frequencies of peaks stay the same.

4.2.13 Pustá Ves

The spectra (see Fig. 37) and the signal in time domain look normal, it means that any artificial influence is not observable and also variability of spectral content between day and night is relatively small. However H/V from night and day (Fig. 38) differs slightly in frequency band about 1 Hz and many not good defined peaks are present.

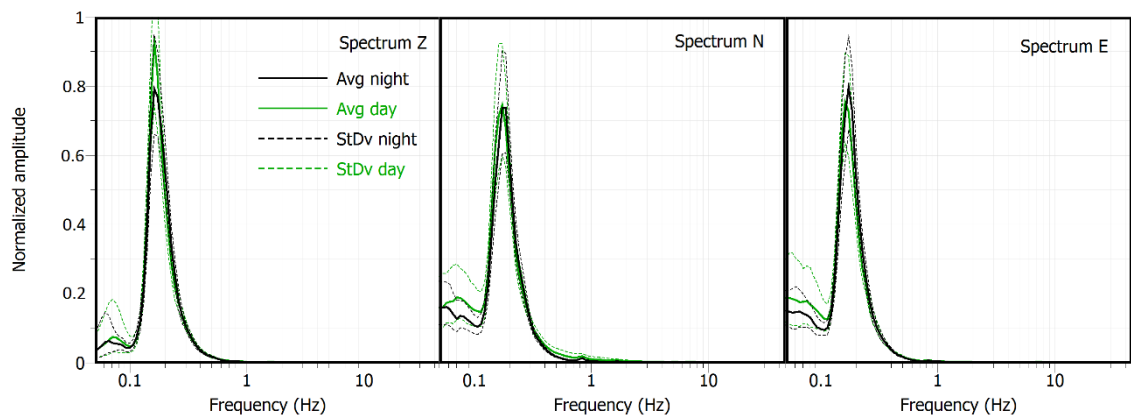


Fig. 37: Normalized spectrum of seismic noise for Pustá Ves seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

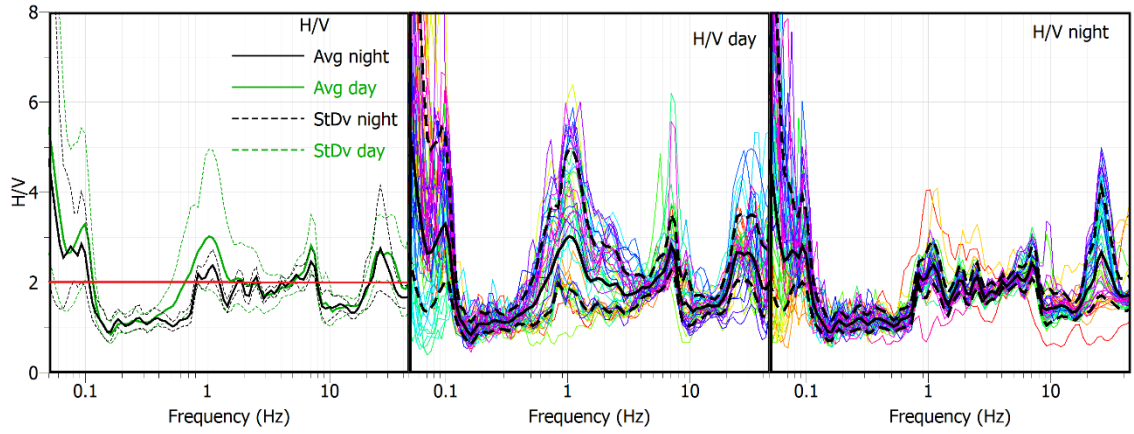


Fig. 38: H/V results for Pustá Ves. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

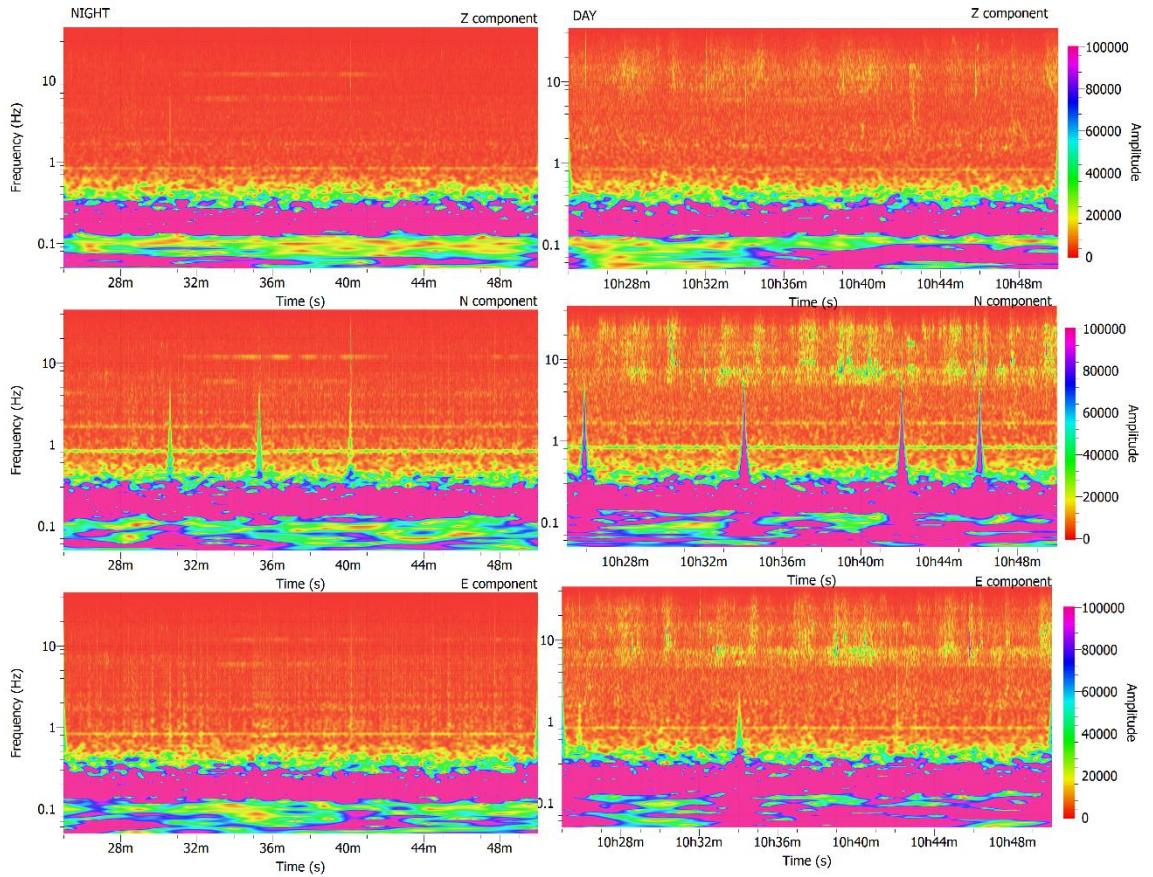


Fig. 39: TFA calculated from 25 minutes long recordings. On the left side is period from the night and on the right side is shown period from daily hours.

The H/V peak at 0.1 Hz is multiple during night, however during day is his frequency well defined. We do not have indication of his artificial origin and this peak will be considered in further analysis. Wide multiple peak which is present during night consists of two peaks, the first peak is at 0.83 Hz and the second is slightly above frequency 1 Hz. Peak at 0.83 is

considered to have artificial origin since on TFA (see Fig. 39) it is present like monochromatic line and because of it we consider in further analysis frequency of daily peak which is more clearly defined. Another peaks of H/V with amplitude slightly above value 2 are at about 7 Hz and at 25 Hz. 7 Hz peak seems to have probably artificial origin while 25 Hz peak looks to be natural and reliable but his frequency during day is not clearly defined. It can be caused by presence of many artificial contribution during daily hours in frequency band roughly from 5 to 25 Hz, it is nicely observable from TFA which is pictured in Fig. 39. On TFA, we can also notice transients reaching from the lowest frequencies through whole frequency range, which occur mainly on N component.

4.2.14 Smolenice

Smolenice (SMOL) seismic station is situated directly in the castle Smolenice and therefore seismic noise is polluted by human activities, what is very nice noticeable from spectra of seismic noise (Fig. 40). Very significant variance of spectral amplitudes mostly at higher frequencies, in frequency band of microtremors, is present. Frequency of microseismic spectral peak is quite solid. However H/V curves (Fig. 41), which are calculated from daily and nightly hours of seismic noise recordings, are very similar. The daily variability is low. Any of the peaks do not satisfy criteria of significance and reliability. In further analysis is considered only flat peak, which is present at lowest frequencies, because he slightly exceeds amplitude two.

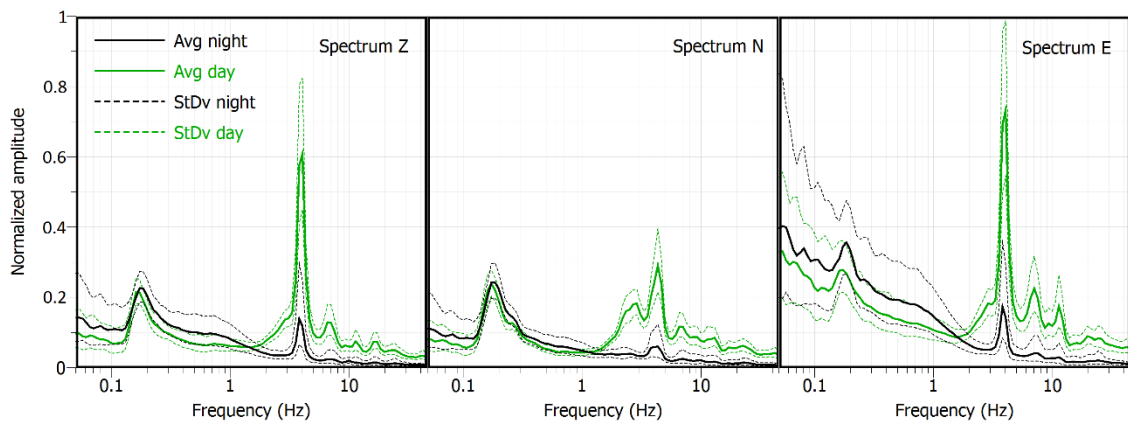


Fig. 40: Normalized spectrum of seismic noise for Smolenice seismic station, from left to right, spectrum of vertical component, north-south, east-west. Green lines match spectrum from daily hours and black lines match spectrum from nightly hours. Solid lines correspond to averaged spectra and dashed lines denote standard deviations.

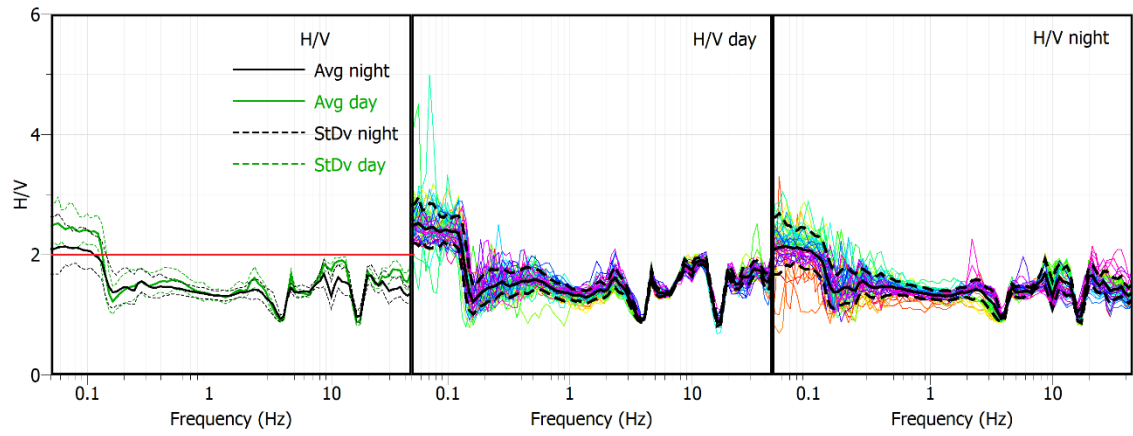


Fig. 41: H/V results for Smolenice. On the left picture is H/V from night (black lines) and day (green lines). Solid lines match average H/V and dashed lines standard deviations of H/V. Red line indicates value two. On the middle picture is H/V from day with H/V curves computed for every time window. On the right picture is H/V from night with H/V curves computed for every time window.

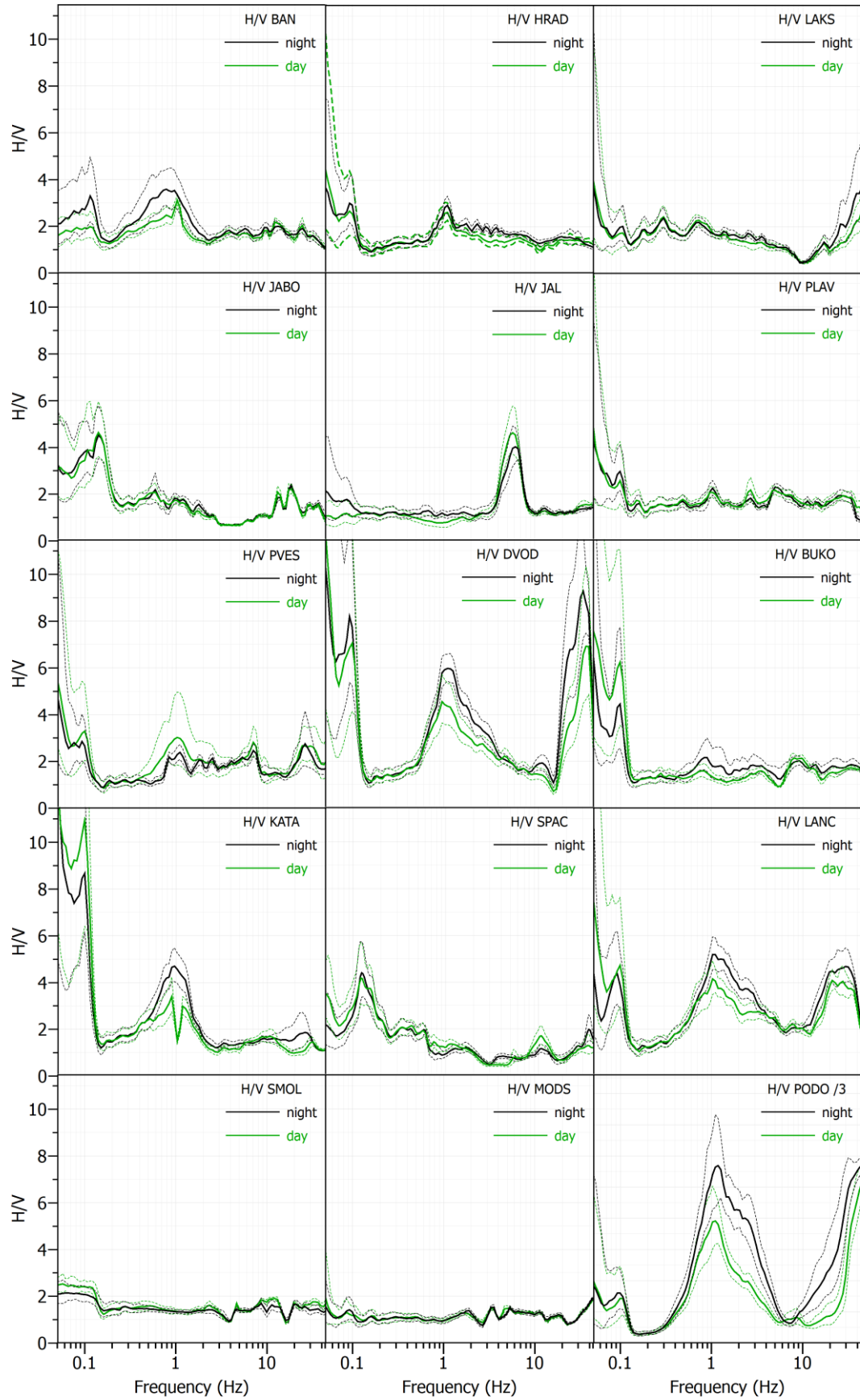


Fig. 42: Summary of H/V results for permanent seismic stations. All results are scaled on the same H/V value 11.5, except of result for station PODO, which is scaled on value 34.5.

4.3 Analysis of H/V spectral ratios from field measurements

In autumn 2015 (06.11.2015) we performed additional seismic noise measurements in order to better cover Malé Karpaty site. We measured the seismic noise at three additional points along the profile through the most significant sedimentary structure in area. One measurement point was in Špačince and the results were already mentioned in the section 4.1.1. The others points were in Bíňovce and Buková, summary information are displayed in *Table 3*.

H/V spectral ratio and spectra from field measurement are computed from 100 seconds long time windows. We reduced duration of time windows in order to have sufficient number of time windows, since during measurement several transient events occurred, which we reject from recordings. Others parameters stay set the same as for calculation from seismic noise recorded by permanent seismic stations (see section 4.2.1). Seismic noise was recorded by two sensor synchronously, by Lennartz (1 s) and Guralp (10 s). From results we can check influence of sensor type on H/V results, it can help us in further interpretation of H/V results

<i>Measurement point</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Type of sensor 1</i>	<i>Type o sensor 2</i>
Buková (BUKOf)	48°32.855`	17°22.981`	Lennartz 1 s	Guralp 10 s
Bíňovce (BINOf)	48°30.332`	17°28.406`	Lennartz 1 s	Guralp 10s

Table 3: Information about point of field measurements. Name of measurement point, latitude, longitude, type of. Seismic sensor 1, type of seismic sensor 2.

4.3.1 Buková

The first point of measurement was selected near to village Buková (BUKOf). Time of recording was about lunchtime of working day and duration of recording was about 1 hour.

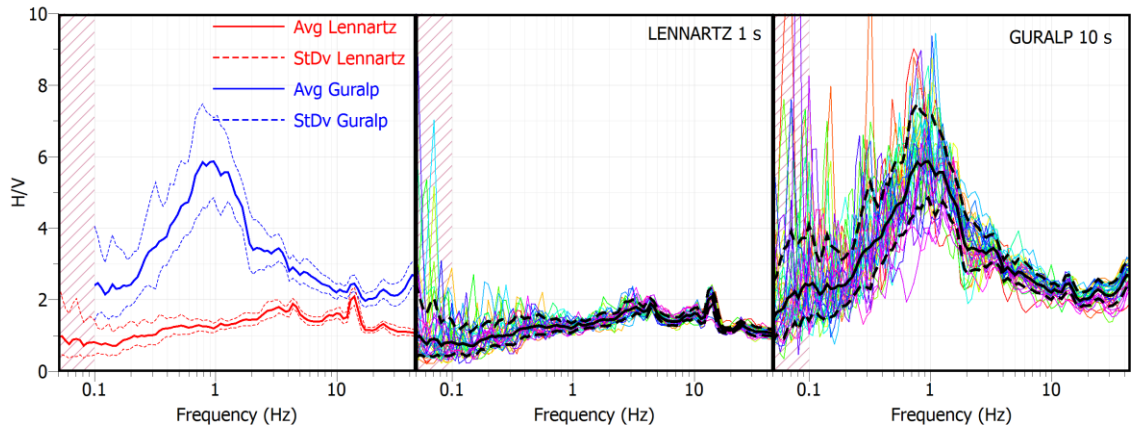


Fig. 43. Comparison of H/V results from site BUKOf. On the most left side are both H/V – red colour marks H/V results from recordings of Lennartz and blue colour marks H/V results from recordings of Guralp sensor. The second picture from left shows H/V from Lennartz, in right picture is H/V from Guralp; colour curves match H/V computed from individual time windows. Solid lines are average values and dashed lines are standard deviations. Shaded region marks unreliable frequency range.

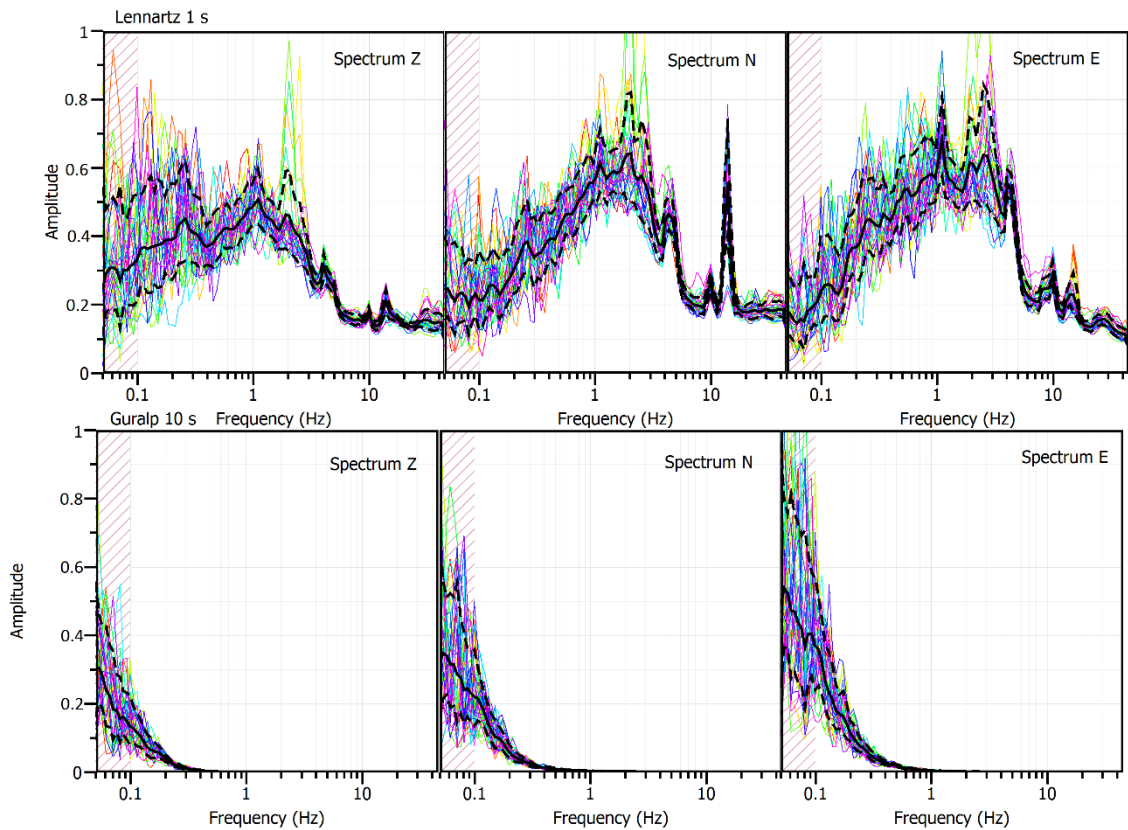


Fig. 44: Spectra from BUKOf. Upper spectra are from Lennartz (1 s) and down are spectra from Guralp (10 s).

In Fig. 43. we can see very significant differences between H/V curves. We suppose that one (or maybe both) of sensors was not recording correctly, probably longer time for stabilization was needed. In spectral domain (see Fig. 44) of data from Lennartz we can notice very suppressed amplitudes at frequencies under 1 Hz, the same is observable on TFA (see Fig. 45). Recording from Guralp sensor has long period trend, which affects spectra

and causes asymptotic increase of spectral amplitudes at the lowest frequencies. However, under some conditions is possible to retrieve reliable H/V at low frequencies also by using short period sensor, but this is obviously not that case. Seismic noise from Lennartz is significant suppressed and we do not consider his H/V results to be reliable. More reliable seems to be H/V from Guralp's recording, which has one significant peak at about 1 Hz. A peaks at the lowest frequencies can be affected by long periodic trend of the recording.

Peak at about 14 Hz seems to be common for both curves. Also just a hint of peak at about 4.5 Hz appears to be common for both H/V. However, these peaks appear to have industrial origin.

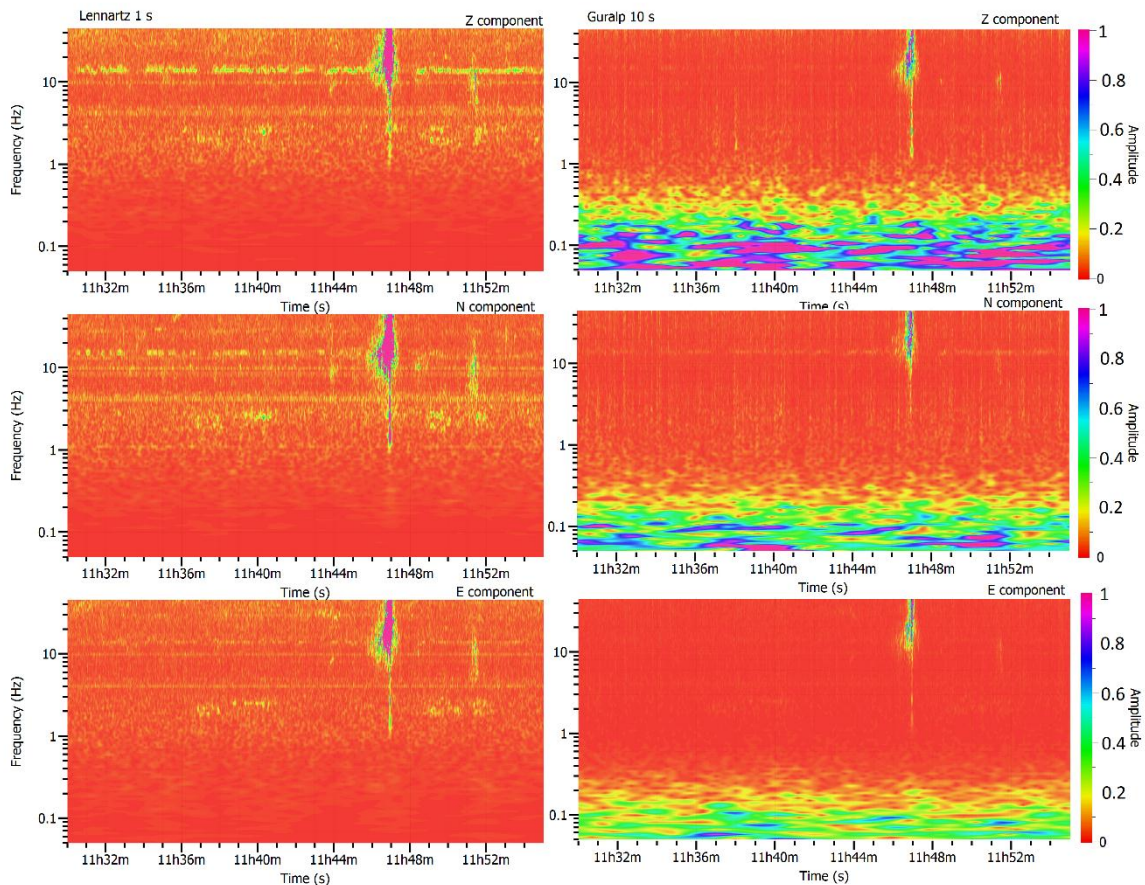


Fig. 45: TFA for the same 25 minutes long period. On the left side results for Lennartz, on the right side for Guralp.

4.3.2. Bíňovce

The seismic noise measurement in Bíňovce (BINOf) was performed on afternoon hours and measurement lasted approximately one hour.

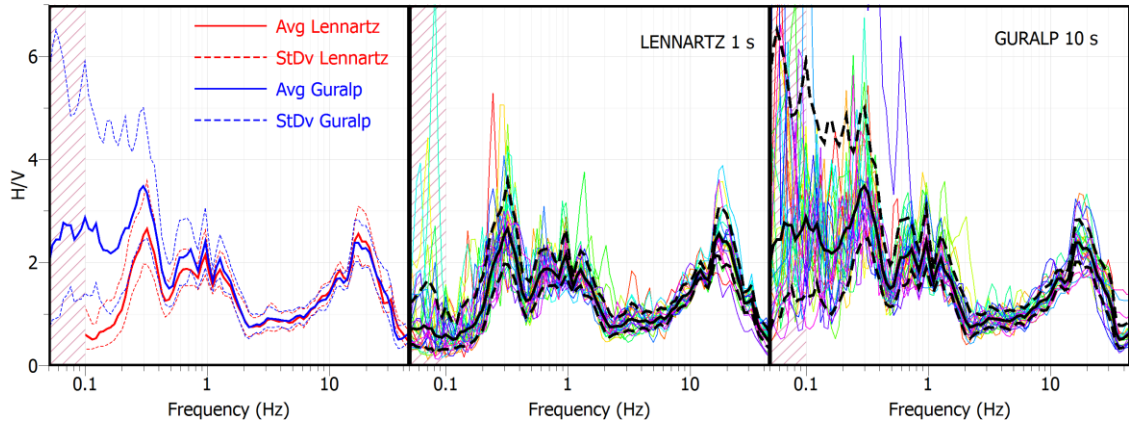


Fig. 46. Comparison of H/V results for BINOf. On the most left side are both H/V – red colour marks H/V results from recordings of Lennartz and blue colour marks H/V results from recordings of Guralp sensor. The second picture from left shows H/V from Lennartz, in right picture is H/V from Guralp; colour curves match H/V computed from individual time windows. Solid lines are average values and dashed lines are standard deviations. Shaded region marks unreliable frequency range.

Recording from sensor Guralp has strange long period trend (as in case of BUKOf) which influences the lowest frequencies. The H/V from Lennartz data has very low variance at low frequencies, because of character of sensor transfer function, which decreases below 1 Hz. Shape of both H/V curves at higher frequencies are quite consistent.

In Fig. 46 are shown H/V results from both sensors. Peak at about 0.3 Hz has stable frequency and it is clear peak, which satisfies all criteria of reliability, as well higher frequency peak at about 17.5 Hz seems to be reliable. Multiple peak centred at 1 Hz with amplitude slightly above value 2, is transformed into broad peak centred about 0.8 Hz after recalculation with smaller smoothing constant (it means stronger smoothing). Since this peak has small standard deviation, one may consider the possible link with a sloping underground interface.

In Fig. 47 are displayed spectra of seismic noises which is recorded by both sensors. Very different character is caused by different transfer functions of sensors – Spectra from Lennartz are suppressed under 1 Hz. And moreover spectra from Guralp are at the lowest frequencies affected by long period trend of recording.

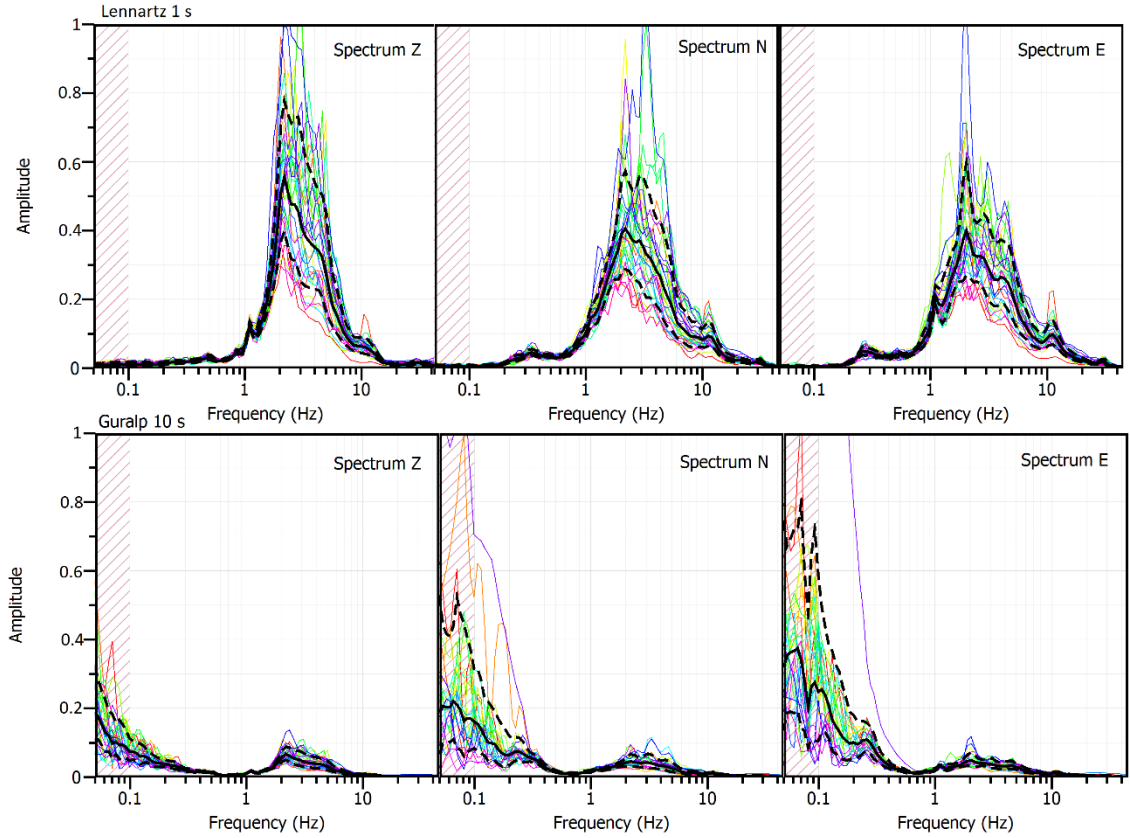


Fig. 47: Spectra of seismic noise from field measurement BINO. Up are spectra calculated from seismic noise recorded by Lennartz (1 s) sensor and down are spectra from seismic noise recorded by sensor Guralp (10 s).

4.4 Calculation of ellipticity curves and SH transfer functions for 1D approximations of local site conditions

In this section we will summarize our results from comparison H/V spectral ratios calculated from recorded seismic noise with fundamental mode of ellipticity curves and SH transfer functions computed for seismic model of Malé Karpaty source zone. The composition of seismic noise wavefield is not well known. However, it is known that the H/V should be influenced mainly by SH resonance in superficial layers and in case of predominance of Rayleigh waves, the ellipticity strongly dictates character of H/V. Therefore we compare H/V curves with both, SH transfer functions and ellipticity curves. We consider only frequencies of the reliable peaks of natural origin, since the absolute value of amplitude of the H/V curve cannot be directly link with amplitude of the ellipticity curve or SH transfer function.

Ellipticity of Rayleigh wave can be calculated as ratio of spectral amplitudes of the longitudinal (so called radial) and vertical component of recording (*Aki and Richards, 1980*) In our work we used for calculation of ellipticity curves program GPELL from program's package of software Geopsy. Details of computation are described in paper by *Wathelet (2005)*.

SH transfer function is computed as a ratio of Fourier spectrum of the signal at the free surface to the Fourier spectrum of the input signal. We computed SH transfer functions firstly using program of software Geopsy GPSH, but it was shown that computed results are not correct. We used Fortran's program Site_trf.exe created by doc. J. Kristek, which uses subroutine of program Micro94 created by *prof. V. Červený*. SH transfer functions are calculated using Thomson-Haskell matrix method. Thomson-Haskell matrix method is used for 1D wave propagation in a 1D layered model. Incidence of the plane wave and delta function as an input signal are considered.

4.4.1 Comparison of results

Theoretical curves have been computed for 1D approximations of currently used 3D velocity model *Geofyzika Brno (1985)*, which were created within projet VEGA 2/0188/15 (Seismic regime in the Malé Karpaty focal zone, 2015-2018) by Dr. M. Kristeková and were provided to us for this work. Assumed value of velocities ratio used for calculation is $v_p / v_s = 1.732$. Values of quality factors for S-waves an P-waves were calculated as $q_s = v_s / 10$ and $q_p = 2 \cdot v_s$. Density was calculated using Gardner's formula $\rho = 0.31 \cdot v_p^{1/4}$ (*Gardner et al., 1974*).

In following pictures *Fig.48 – Fig.64* are shown comparisons of observed H/V curves with theoretical curves for every permanent stations and also for field measurements BUKOf and BINOf.

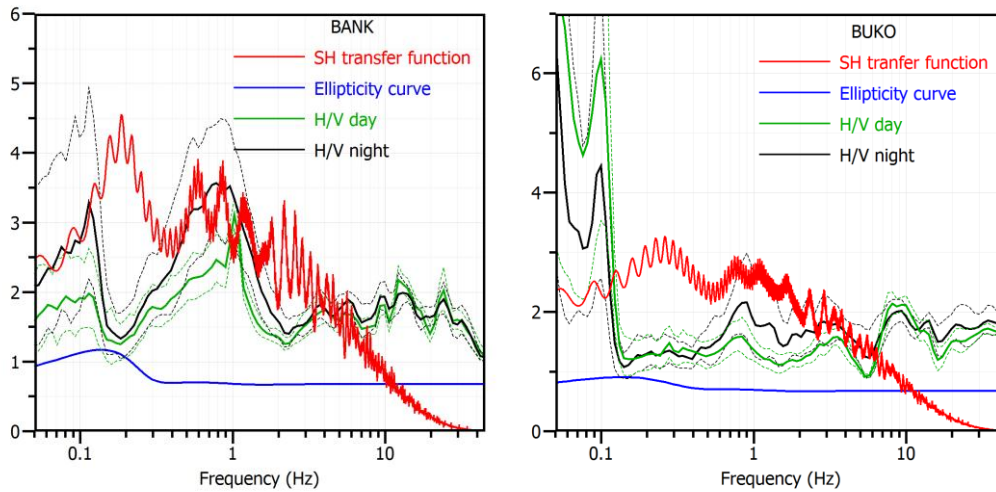


Fig. 48 & Fig. 49: Comparison of observed H/V with theoretical curves for seismic station BANK (on the left) and BUKO (on the right).

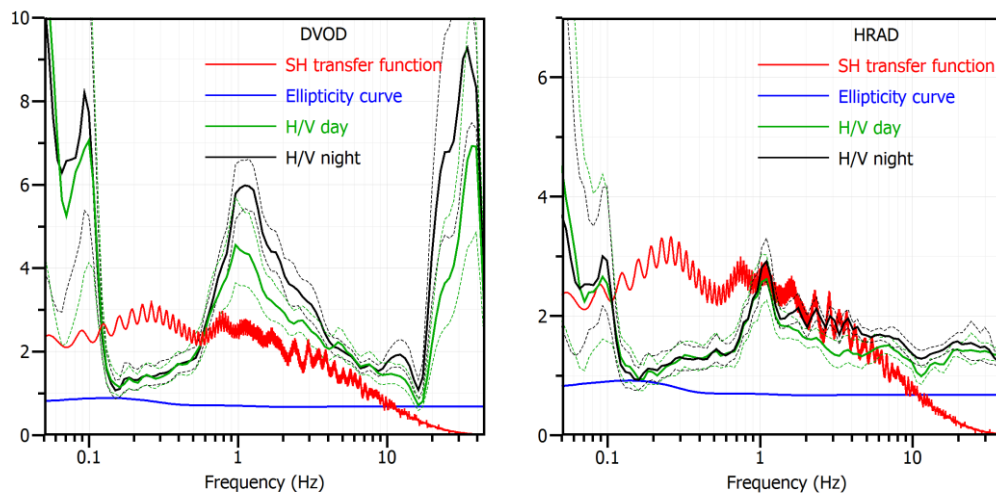


Fig. 50 & Fig. 51: Comparison of observed H/V with theoretical curves for seismic station DVOD (on the left) and HRAD (on the right).

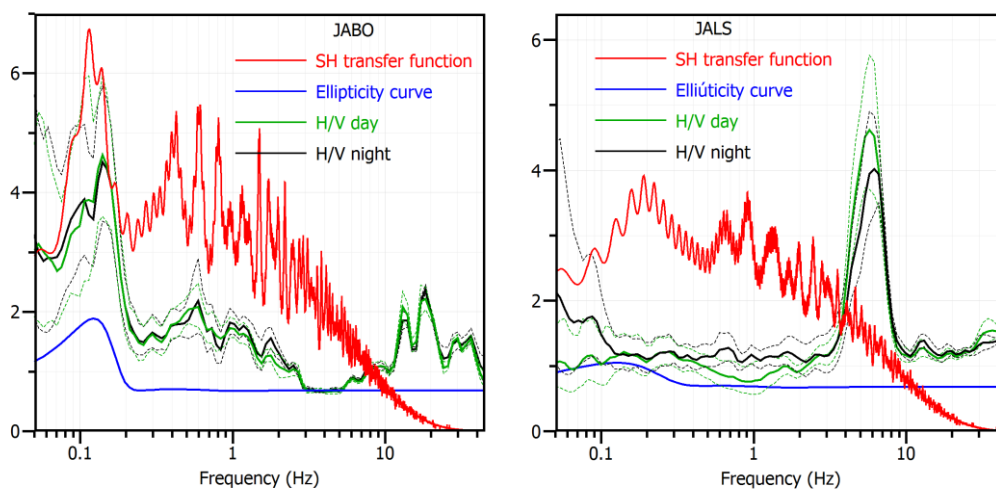


Fig. 52 & Fig. 53: Comparison of observed H/V with theoretical curves for seismic station JABO (on the left) and JALS (on the right).

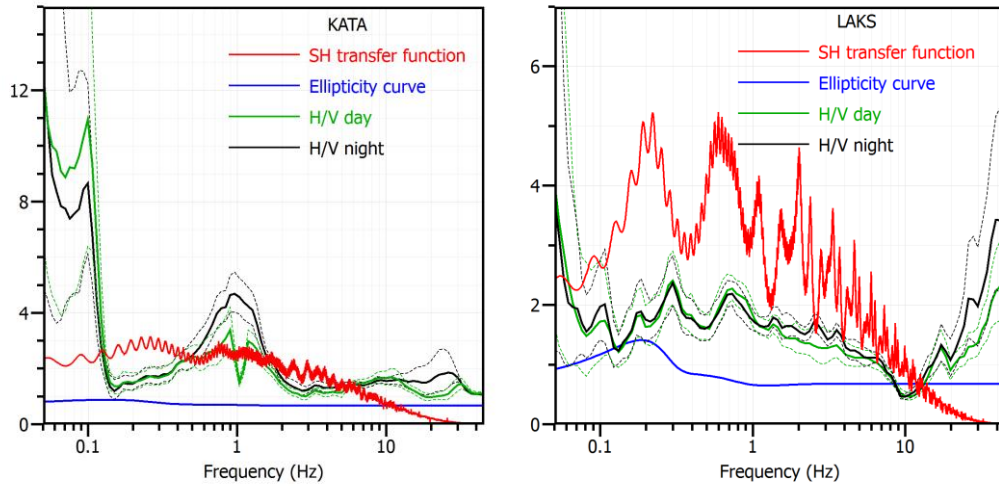


Fig. 54 & Fig. 55: Comparison of observed H/V with theoretical curves for seismic station KATA (on the left) and LAKS (on the right).

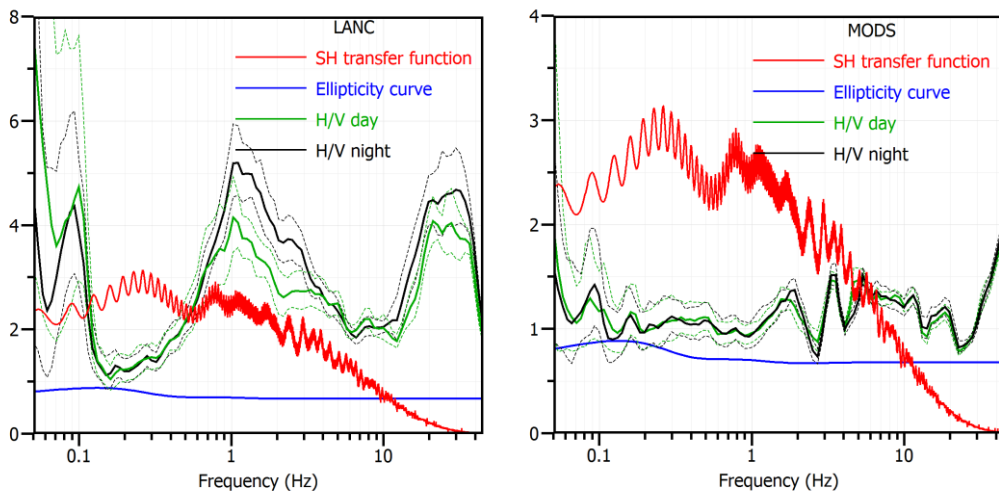


Fig. 56 & Fig. 57: Comparison of observed H/V with theoretical curves for seismic station LANC (on the left) and MODS (on the right).

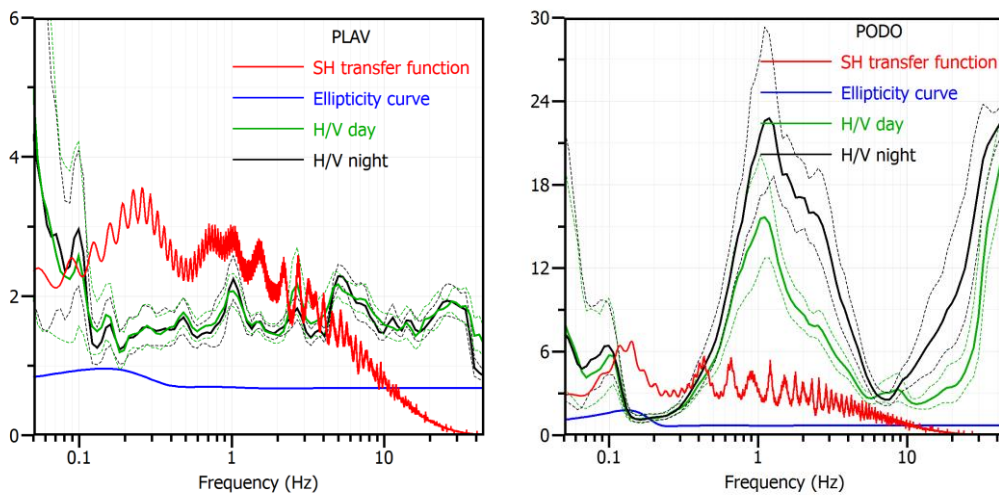


Fig. 58 & Fig. 59: Comparison of observed H/V with theoretical curves for seismic station PLAV (on the left) and PODO (on the right).

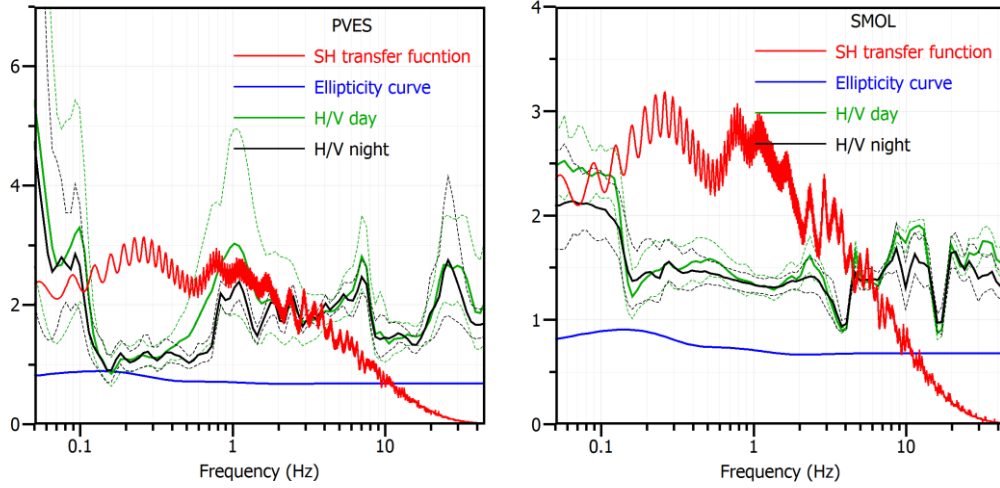


Fig. 60 & Fig.

61: Comparison of observed H/V with theoretical curves for seismic station PVES (on the left) and for SMOL (on the right).

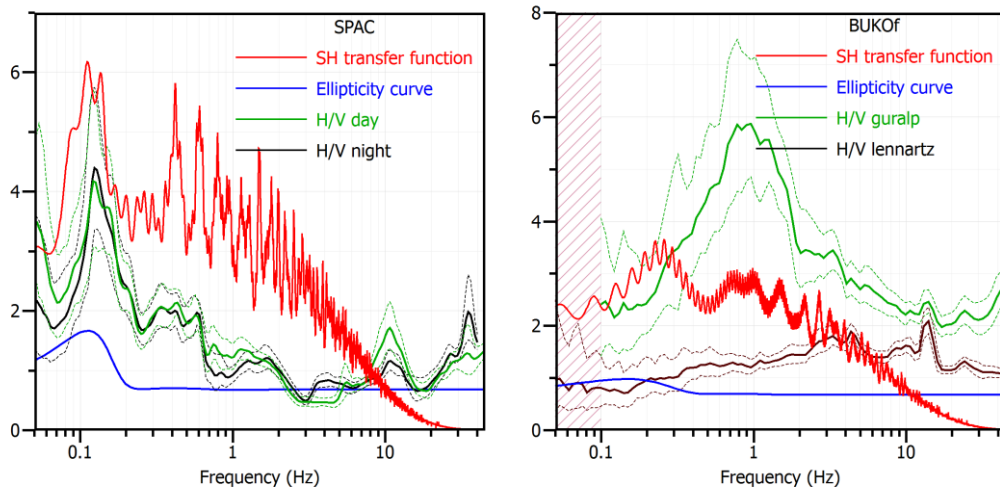


Fig. 62 & Fig. 63: Comparison of observed H/V with theoretical curves for seismic station SPAC (on the left) and for field measurement BUKOf (on the right).

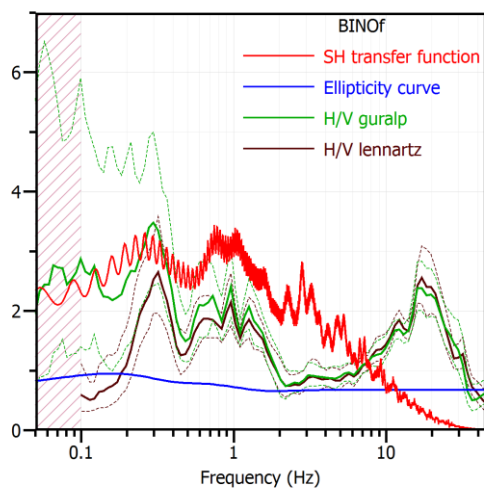


Fig. 64: Comparison of observed H/V and theoretical curves for field measurement BINOOf.

The H/V results for majority of the permanent seismic stations exhibit peak at about 0.1 Hz (with slightly frequency variations) more or less clear and significant. Low frequency peak above 0.1 Hz, however shifted to higher frequencies, can be seen also on computed ellipticity curves. Frequencies of low frequency (LF) peaks identified on both observed H/V and theoretical ellipticity curves for every seismic station are displayed in *Table 4*.

<i>Seismic station</i>	<i>Frequency of H/V peak (Hz)</i>	<i>Peak quality</i>	<i>Amplitude of H/V peak</i>	<i>Frequency of ellipticity peak</i>
BANK	0.1140	good	3.25	0.1311
BUKO	0.0990	very good	4.38	0.1381
DVOD	0.0927	very good	8.14	0.1311
HRAD	0.0947	good	3.00	0.1385
JABO	0.1443	good	4.50	0.1219
JALS	0.0860	not good	1.75	0.1385
KATA	0.1000	very good	8.65	0.1298
LAKS	0.1031	not good	2.00	0.1900
LANC	0.0915	good	4.34	0.1284
MODS	0.0914	not good	1.97	0.1285
PLAV	0.1000	good	2.91	0.1424
PODO	0.0951	good	9.81	0.1311
PVES	0.0927	good	2.81	0.1309
SMOL	0.1000	not good (plateu)	2.12	0.1402
SPAC	0.1248	very good	4.35	0.1118

Table 4: Summary information about peaks at about 0.1 Hz from H/V and from ellipticity curve: Name of seismic station, frequency of H/V peak, Peak quality - denotes qualitative characteristic of H/V peaks, amplitude of H/V peak, frequency of peak from ellipticity curve.

In order to better investigate spatial variation of the fundamental frequency of the low frequency (LF) peaks we have plotted figures with a map view where symbols at the position of each station are colour coded according to the identified peak frequency. Spatial variation of observed LF H/V peak is shown in *Fig. 60* and in *Fig. 61* there is shown a spatial variation of frequency of ellipticity peaks calculated from available seismic model. On the x and y axes of *Fig. 65 – 67* are Cartesian spatial coordinates, so called JTSK. From

Fig. 65 we can see that frequency variability of H/V peak fairly well fits shape of the deep sedimentary valley and also those parts of the model corresponding Male Karpaty, Mts. (see Fig. 1 in section 1.3). Roughly similar spatial variability can be observed from Fig. 66 for the peak of theoretical ellipticity. In order to better see whether the frequency shift between observed H/V results and those of ellipticity peak is consistent for all stations there are shown also the differences between frequency of H/V peak and frequency of theoretical peak from ellipticity curves in Fig. 67. From picture it can be seen that the highest differences are for seismic station LAKS while the smallest differences are for seismic stations JABO, SPAC and BANK.

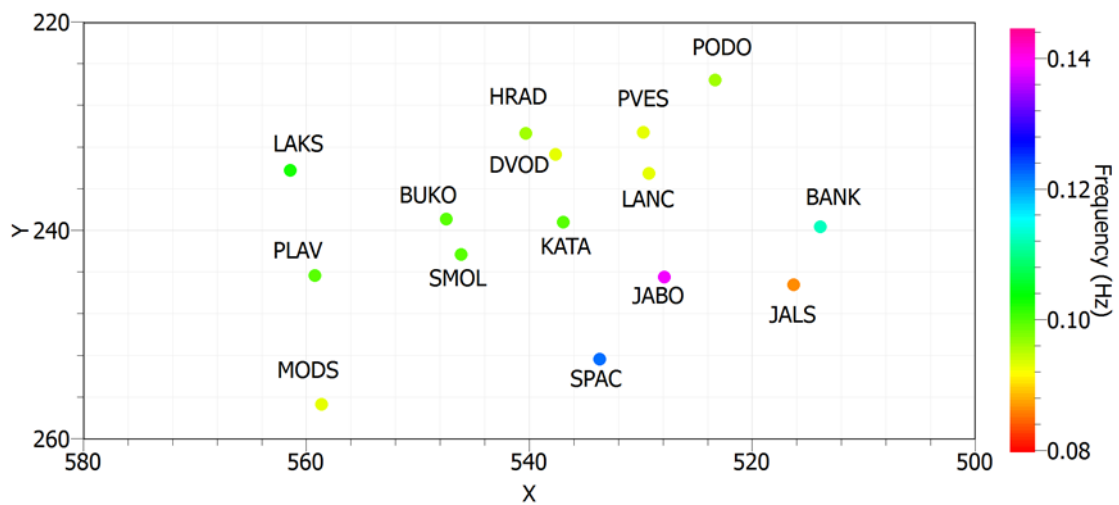


Fig. 65: Map of frequency variability of H/V peak at about 0.1 Hz for seismic stations in Malé Karpaty source zone.

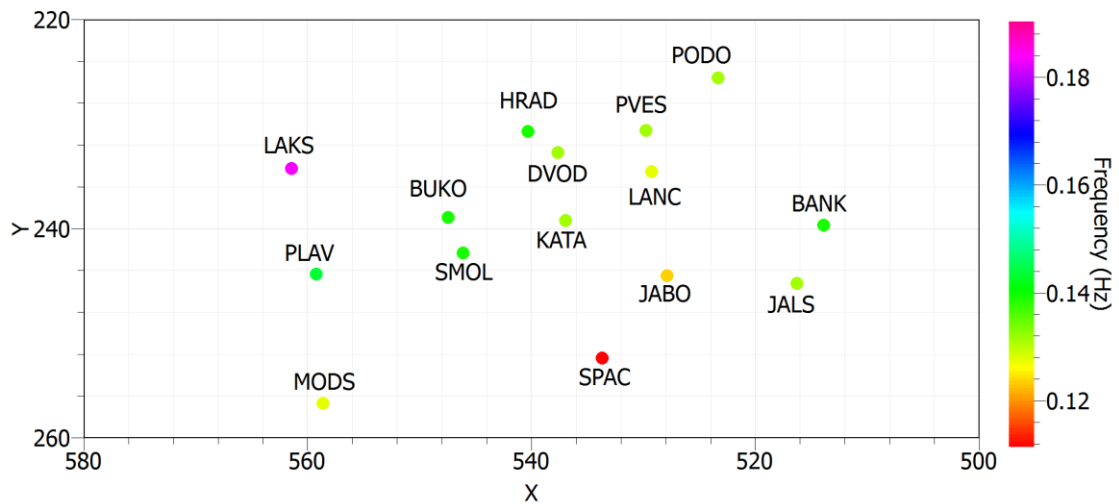


Fig. 66: Map of frequency variability of peak at about 0.1 Hz from ellipticity curves for seismic stations in Malé Karpaty source zone.

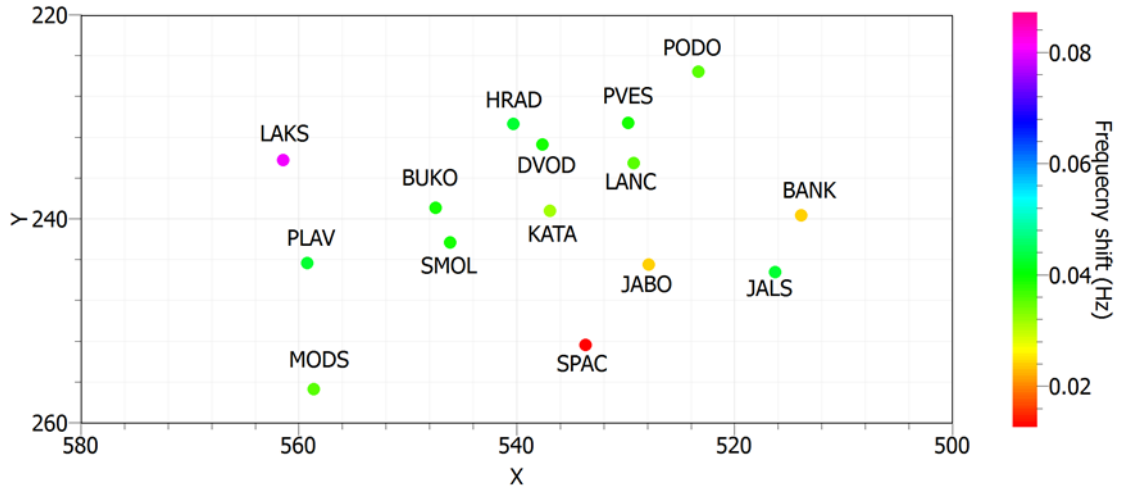


Fig. 67: Map of frequency differences between H/V peak and peak of ellipticity curve for seismic stations in Malé Karpaty source zone.

The SH transfer functions for almost every stations exhibit peak at about 0.25 Hz, but none of H/V does not exhibit peak at this frequency. On stations JALS, BANK, LAKS the peak of SH transfer function is shifted to slightly lower frequency at about 0.2 Hz, but H/V does not exhibit peak at the same frequency neither. And to the even lower frequencies – SH transfer function peak at about 0.15 Hz is shifted for stations SPAC, JABO, PODO. For JABO and SPAC there is relatively good agreement with the observed H/V peak (also ellipticity curve exhibits the peak at the same frequency) while for PODO, the H/V does not exhibit peak at the same frequency.

Another common feature of observed H/V curves is peak at about 1 Hz, which occurs at the most of seismic stations. On the seismic stations DVOD, PODO, KATA, LANC 1 Hz peak is very significant, dominant and relatively wide. On the stations HRAD, PLAV and PVES it is well defined but not so significant and on station JABO is not well define but some hint of peak is present. The H/V from other stations LAKS, JAL, BUKO, SPAC, SMOL, MODS does not exhibit such peak at above frequency 1 Hz. Peak at about 1 Hz is at the most cases exhibited also on theoretical SH transfer functions.

The H/V curves from several stations exhibit also high frequency peak. Peaks at the high frequency respond to shallow interfaces. Model of source zone Malé Karpaty does not contain information about such a shallow region of geological structure therefore any of the theoretical curves do not exhibit the high frequency peak. The H/V indicates that for the area of stations DVOD, LANC, PVES there can possibly be some thin layers in shallow

region of structure, since high frequency peak is present. Moreover these seismic stations are neighbouring (see e.g. Fig. 67) what can suggest that these peak are associated with something typical for this part of area and gives suggestion for improvement of the existing seismic model.

Another significant peak which is not fitted by model is peak about 6 Hz for station JALS.

From the above presented results we can see that overall agreement of observed H/V ratios derived from seismic noise recordings with theoretical curves calculated for 1D approximations of currently used 3D model of source zone Malé Karpaty, is not sufficient. While the best match of observed H/V and theoretical curves is observed on station JABO and SPAC.

4.4.2 Tests of influence of model's parameters selection

In this section we show examples of influence of model's parameters selection on theoretical curves.

Since 3D velocity model (Geofyzika Brno, 1985), which has been used for creation of 1D approximations, contains only P-wave velocities, others parameters which are needed for computation of theoretical curves have to be calculated using empirical formulas (see Subsection 4.4.1). But their selection is not always clear.

Based on conference's contribution by *Fojtíková et al. (2016)* we have tested calculation of theoretical curves also using value $v_p / v_s = 1.89$ instead of $v_p / v_s = 1.732$, while the value of v_p is known from model. Others formulas stay the same, but change of velocity's ratio formula affects also other model's parameters. Comparison of theoretical curves for 1D model of HRAD which are calculated using different values of S-waves velocity are shown in *Fig. 68*. In *Fig. 68* we can see that change of above mentioned formula has not significant effects on results of theoretical curves. We can observe just slight shift of curves HRAD v2 to the lower frequencies against curves HRAD v2.

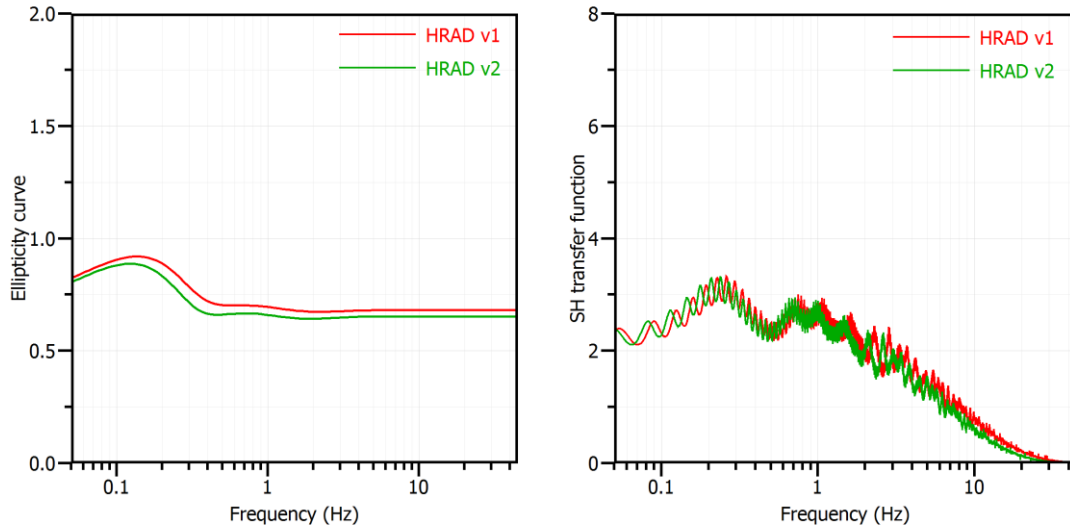


Fig. 68: Comparison of theoretical curves using different S -waves velocity. Curve HRAD v1 is calculated using $v_s = 1.732 * v_p$ (red lines) and HRAD v2 is calculated using $v_s = 1.89 * v_p$ (green lines) for 1D model of seismic station HRAD. On the left side is comparison of ellipticity curves, on the right side comparison of SH transfer functions.

In general two formulas exist for calculation of S -wave quality factor. For calculation of theoretical curves (see Subsection 4.4.1) we used $q_s = v_s / 10$. Here we compare the results with theoretical curves calculated using the second formula $q_s = v_s / 20$. This change has effect also on quality factor of P -waves. The others model's parameters are the same. In Fig. 69 is shown comparison for 1D model approximation of seismic station JABO. We can see that change of formula for S -wave quality factor causes difference of ellipticity curve, which is within size of line. Smaller quality factors used in model are reflected by the bigger attenuation at the higher frequencies of SH transfer functions.

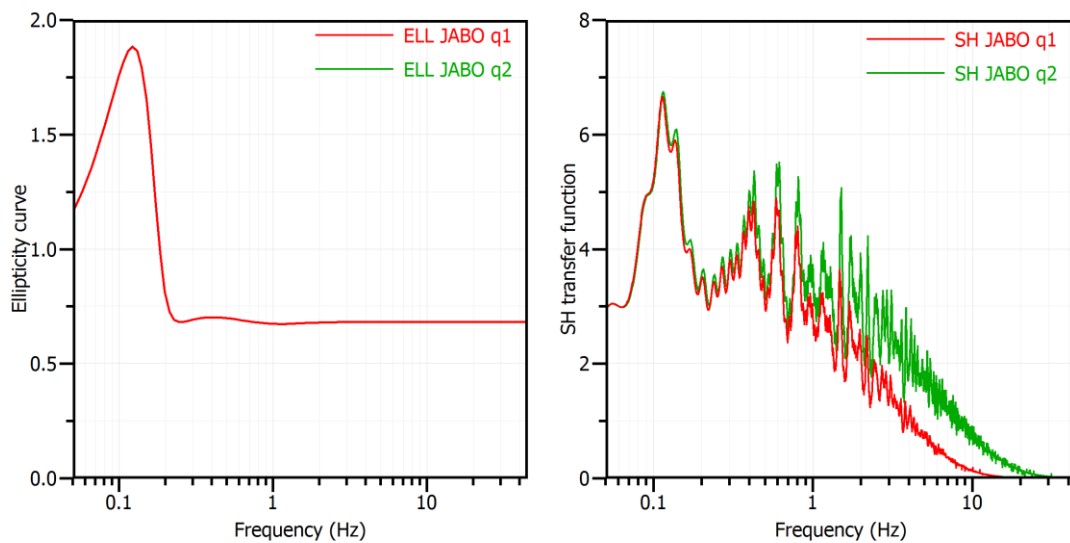


Fig. 69: Comparison of theoretical curves using different formula for quality factor of S -waves. JABO q1 is calculated using $q_s = v_s / 10$ (red lines) and JABO q2 is calculated using $q_s = v_s / 20$ (green lines) for 1D model of seismic station JABO. On the left side is comparison of ellipticity curves, on the right side comparison of SH transfer functions.

In Fig. 70 is shown comparison of theoretical curves calculated for 3 different average models of source zone Malé Karpaty, which are also used for this area. Model DV_fast are for all stations of source Malé Karpaty expect of stations JABO and SPAC. For these two station average model DV_slow is considered. Velocity model Tect_2010 is model used in study *Fojtíkova et al. (2016)* after model published in *Fojtíková et al. (2010)*.

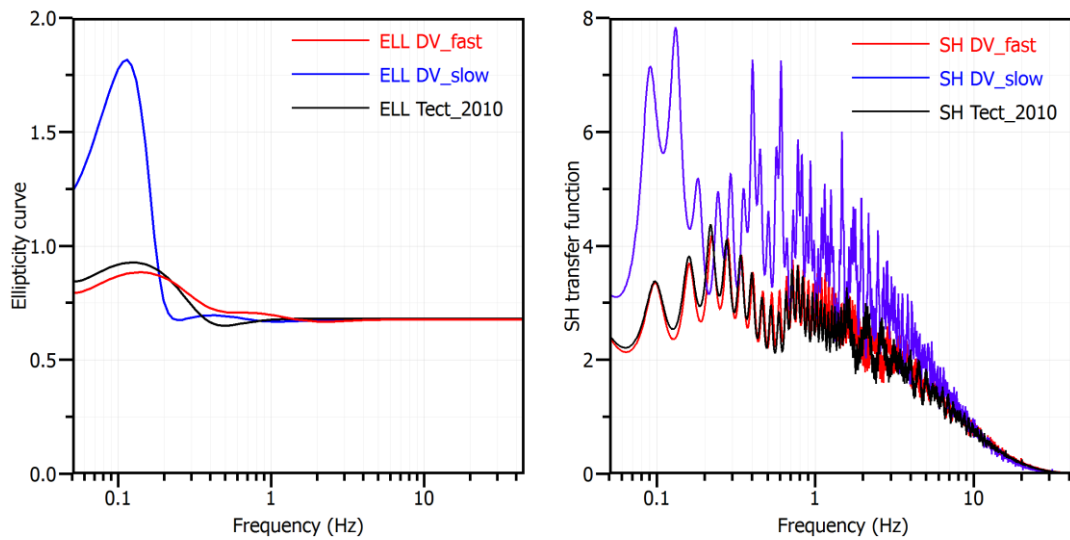


Fig.

Fig. 70: Comparison of theoretical curves calculated for different models: DV_fast (red lines), DV_slow (blue lines) and Tect_2010 (black lines). On the left side are ellipticity curves and on the right side are displayed SH transfer functions.

Conclusions

We have analysed seismic noise recorded at the permanent seismic stations of local seismic network Malé Karpaty using the H/V spectral ratio method.

We have compared the obtained results with theoretical ellipticity curves and SH transfer functions, computed for the currently used seismic model of the area,

We have analysed and discussed the nature of the differences in terms of validity of the seismic model of the area.

Besides the above three main tasks we have also focused on the following complementary subtasks:

- We have investigated all year variability of spectral content of seismic noise and of H/V results at the selected seismic station. Our results demonstrate the necessity to perform investigation of long term noise variability. Such analysis also helps to identify frequencies in the seismic noise affected by anthropogenic noise sources.
- We have compared the results obtained by common way of H/V spectral ratio with those obtained by the computation according to *Albarelli & Lunedei (2013)* and we have found no significant differences between the results of both approaches. Test with different ways of merging of horizontal components also showed that the way of merging did not influenced the results.
- We have identified and excluded the peaks of artificial origin in the obtained H/V results for each station.
- We tested influences of some model's parameters on resulting theoretical curves
- We have calculated ellipticity curves and SH transfer functions for 1D approximations of currently used 3D velocity model of source zone Malé Karpaty beneath the seismic station.

- We have performed field measurements of seismic noise in 2 additional measurement points in the source zone Malé Karpaty using two sensors with different frequency characteristics simultaneously. H/V results were also compared with ellipticity curves and SH transfer functions computed for the site of measurement. We compared also influences of different sensors on the results of H/V spectral ratio.

To briefly summarize the main results, the level of agreement between observed H/V and the theoretical curves (ellipticity and SH transfer functions) shows that the current model needs improvement, the best agreement was at stations EBO and SPAC. Model obviously lacks details in the surface part. Our H/V results and their comparison with the theoretical curves provide basis for the next research of the area and for the future model improvement.

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Addendum

Abstract

*Validation of the 3D seismic model of Malé Karpaty focal zone
using seismic noise spectral H/V method*

We present an analysis of a seismic noise recorded on permanent seismic stations in a source zone Malé Karpaty using H/V spectral ratio method. We also present a comparison of obtained H/V results, calculated from the seismic noise with theoretical ellipticity curves and SH transfer functions, which are calculated for existing seismic model of the area. The source zone Malé Karpaty is one of the most important epicentral areas in Slovakia. It is also one of the most active source zones and its importance is enhanced by the vicinity of the nuclear power plant Jaslovské Bohunice. Monitoring and analysis of the seismicity is essential for a reliable assessment of the seismic hazard of the nuclear power plant. For a reliable estimation of the seismic hazard it is crucial to have detailed information about local geological structure, which is very complex for source zone Malé Karpaty. Moreover, the currently used 3D velocity model is not accurate enough, which has negative impact on the accuracy of the earthquake localization and also on other characteristics of the seismicity on the site. Construction of more accurate model is very important long-term research goal. H/V spectral-ratio method applied to seismic noise should allow us to find the spatial variability of local geological structure. In this work, we summarize the current knowledge about the seismic noise wavefield composition and about methods for analysis of the seismic noise with focus on method H/V spectral ratio. We describe the method in detail. We also describe the relation between the seismic noise wavefield and H/V and the importance of parameters and factors used for the correct interpretation of the obtained results. We analyse seismic noise recordings from all permanent seismic stations of the source zone Malé Karpaty and also from additional field measurement on the two another points. For every seismic station, we calculate H/V spectral ratio, from which we exclude peaks with artificial origin. Then we compare these H/V spectral ratios, with theoretical ellipticity curves and SH transfer function, which are calculated from currently used model.

The comparison and analysis of differences helps us to identify the parts of the model which differ from reality the most. These results will be useful for further investigation of seismic model of source zone Malé Karpaty.

Keywords: method H/V spectral ratio, seismic noise, source zone Malé Karpaty, velocity model, theoretical curves

Abstract

Validierung des seismischen 3D-Modells der Malé Karpaty-Quellregion mithilfe der H/V-Spektralmethode aus seismischem Rauschen

Wir präsentieren eine Analyse des seismischen Grundrauschens an den permanenten seismischen Stationen im Malé Karpaty Herdgebiet, mithilfe des H/V-Verhältnisses im Frequenzbereich. Wir erstellen einen Vergleich der erhaltenen H/V-Ergebnisse, die aus dem seismischen Grundrauschens mit theoretischen Elliptizitätskurven berechnet wurden, mit SH-Übertragungsfunktionen, die aus existierenden seismischen Modellen der Gegend bestimmt worden sind. Das Malé Karpaty-Herdgebiet ist eines der wichtigsten Erdbebengebiete in der Slowakei. Es ist auch eines der aktivsten Herdgebieten, dessen Bedeutung durch die Nähe des Kernkraftwerks Jaslovské Bohunice unterstrichen wird. Überwachung und Analyse der Seismizität ist unerlässlich für eine zuverlässige Beurteilung der seismischen Gefährdung des Atomkraftwerks. Für eine verlässliche Abschätzung der seismischen Gefährdung ist es wichtig, genaue Informationen über die lokale geologische Struktur zu gewinnen, die sehr komplex für das Malé Karpaty-Gebiet ist. Darüber hinaus sind die derzeit verwendeten 3D-Geschwindigkeitsmodelle nicht genau genug, was negative Auswirkungen auf die Genauigkeit der Lokalisierung von Erdbeben hat, wie auch auf andere Merkmale der Seismizität in der Gegend. Das Erstellen eines genaueren Modells ist ein sehr wichtiges langfristiges Forschungsziel. Angewandt auf das seismische Grundrauschen, sollte die Anwendung der H/V-Spektralverhältnismethode es uns erlauben, die räumliche Variabilität der lokalen geologischen Struktur zu bestimmen. In dieser Arbeit fassen wir das aktuelle Wissen über das seismische Grundrauschen und über Methoden zur Analyse dieses Rauschens mithilfe der H/V-Spektralverhältnismethode zusammen. Wir beschreiben die Methode im Detail; wir beschreiben auch das Verhältnis zwischen dem Wellenfeld des seismischen Grundrauschens und H/V und die Bedeutung der Parameter und Faktoren, die für die korrekte Interpretation der Ergebnisse verwendet werden. Wir analysieren Aufzeichnungen des seismischen Grundrauschens von allen permanenten seismischen Stationen des Malé Karpaty-Gebiets, und auch aus zusätzlichen Feldmessungen an zwei anderen Orten. Für jede seismische Station berechnen wir das H/V-Spektralverhältnis, aus welchem wir Peak künstlichen Ursprungs ausschließen. Dann

vergleichen wir diese H/V-Spektralverhältnisse mit theoretischen Elliptizitätskurven und der SH-Transferfunktionen, die aus dem derzeit verwendete Modell berechnet wurden. Der Vergleich und die Analyse der Unterschiede hilft uns, die Teile des Modells zu identifizieren, die von der Realität abweichen. Diese Ergebnisse werden hilfreich für die weitere Untersuchung des seismischen Modells des Malé Karpaty-Herdgebiets sein.

Schlüsselworte: H/V-Spektralverhältnismethode, seismisches Rauschen, Malé Karpaty-Herdgebiet, Geschwindigkeitsmodell, theoretische Kurven

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